THE MEASUREMENT OF POINT DISCHARGE CURRENTS IN A TREE BY THEIR MAGNETIC EFFECT

THESIS

presented by
Randolph Webster B.Sc. (Edin)
for the Degree of
Doctor of Philosophy

JUNE 1952

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List of Contents:

List of Illustrations:

Introduction:

The maintenance of a permanent negative charge by the earth can be regarded as the greatest unsolved problem of atmospheric electricity. The existence of this charge alone may indeed be considered as the basic problem of the subject. Before a complete understanding of all the electrical phenomena that occur in the atmosphere can be achieved, a solution to this problem must be found.

Many of the problems of atmospheric electricity have been solved, but in themselves only fill in some of the detail of the many and varied phenomena that occur. The reason for the existence of a permanent, although variable, electric potential gradient in the atmosphere has remained as yet undiscovered. All the other phenomena may be attributed either directly or indirectly, to the presence of this electric field.

The first person to suggest that the earth was charged was Erman. Working on the same lines as de Sanssure and Volta in investigating the effects of the atmospheric potential field, he showed that the charging of a conductor exposed to the atmosphere could be accounted for by the assumption that the earth itself held a charge. It was Peltier however who showed that the charge was negative. He also put forward a theory that water-vapour, when evaporating, carried away from the earth some of the negative charge, and in this way tried to explain the observed variations in the electric field strength.

William Thomson (later Lord Kelvin) first applied the idea of "potential" to the observations and using the conception of the "electric lines of force" pointed out the necessity of identification of the ends of these lines, if they are assumed to start at the earth's surface. So far this problem has not yet been solved. It is now normally assumed that high up in the atmosphere there exists a highly conducting layer which carries a predominance of positively charged ions. The actual position of this layer has not yet been identified. Since the discovery by the radio-scientists of ionised layers in the upper atmosphere, it has been assumed that the conducting layer is at some similar altitude.

The observations of Linss showed that not only did the earth have a negative charge, but also the air itself, being a conductor, would allow the negative charge to leak away in about ten minutes. This fact thus raises the basic question as to how the earth manages to maintain its negative charge.

The only method by which the earth can

maintain its charge is by the return of an equal and opposite amount of charge at some place other than where the leak of negative charge is taking place. Professor C.T.R. Wilson was the first to notice the significance of the variations of the electric field, especially these variations that changed the direction of the potential gradient. He was the first to propose that the earth received a negative charge from the atmosphere in thunderstorm conditions. This idea was a result of his observations of the potential field at the earth's surface during thunderstorms.

The correlation of the daily variations of the atmospheric potential gradient and the total thunderstorm activity over the earth's surface was carried out by Whipple. The result of this work was so striking that there could be little doubt but that Wilson's idea was the solution to the problem. The variations of the potential gradient indicate maxima at exactly the same time as the maxima of thunderstorm activity. Considering the earth and the conducting layer in the upper atmosphere as conductors of zero resistance,the maximum electric field would of necessity coincide with the arrival of the greatest amount of negative charge at the earth's surface. The maxima of potential gradient coincides with the maxima of the storm activity. It can therefore safely be assumed that the arrival of negative charge at the earth's surface is due to the storm activity.

The interest in atmospheric electricity at this point not unnaturally was turned to the investigation of the thunderstorm. Observations of the electric field showed that during a thunderstorm the normal positive electric field is in the majority of cases reversed and the earth below the storm may be shown to be positively charged.

Observations on the field changes taking place immediately after a lightning flash indicated that in general the base of the thunderstorm held a negative charge or pole. The upper layers of the thunderstorm likewise may be shown to contain a positive pole. These conditions were not found to be invariable, but the results of many observations indicated they were the most frequent.

The existence of the polarisation of the thunderstorm, immediately raised the question as to how the charge is separated within the cloud. Numerous theories were proposed by Gerdien, Elster and Geitel, Simpson and Professor C.T.R. Wilson, but of these only that of Professor Wilson has achieved general acceptance.

Professor Wilson's theory (1) is based on the polarisation of the cloud droplets and rain drops in the normal positive electric field. The process of charge separation takes place by ion capture by the water droplets. Ions of both signs exist in the atmosphere. A rain drop falling through the cloud is polarised by the normal fair weather field in such a way that the top of the drop carries a negative charge, the base carrying a positive charge. The nett charge on the drop is initially zero.

Under the influence of the electric field the negative ions will be moving upwards and the positive ions downwards. A rain drop, falling with a suitable velocity will thus pick up negative charges at its base. Positive ions, moving downwards, may not have sufficient velocity to catch up with the falling drop, and those overtaken by the drop are repelled by the positive charges at the base. A suitable choice of velocity for the falling drop can therefore make the collection of positive charges impossible. The falling drop thus acquires a negative charge.

The rising cloud droplets, will be similarly polarised and on meeting the descending positive ions will also charge by ion capture. The nett charge gained in this case will be positive. In this way the cloud may be considered as separating out the charge required for the development of a thunderstorm.

By the Wilson process any convection cloud can be assumed to be capable of development into a thunderstorm provided the conditions of the ion and drop velocity are correct. We may therefore expect that shower clouds exhibit the same electrical structure as a fully developed thunderstorm. This has been shown to be the case.

The beauty of Professor Wilson's theory lies in its simplicity. The theory however also explains the existence of a predominance of positively charged raindrops on their arrival at the earth's surface during a heavy shower or thunderstorm.

The result of the Wilson process of charge separation is the production of a positively polarised thunderstorm or cumulo-nimbus cloud. Positive polarisation of a thunderstorm means that the top of the cloud maintains a positive charge centre or pole and the base a negative pole.

The passage of such a cloud over an observer measuring the electric field at the ground would cause a definite and regular change in the potential gradient. Initially the positive fair weather field would exist and as the cloud approached this positive field would first show a slight increase. The closer approach of the thunderstorm would show a progressive decrease of the positive field and a reversal to negative values as the edge of the cloud passed overhead. The passage of the negative pole of the cloud base would give rise to high values of negative potential gradient. As the cloud moves away the reverse of this change would take place, until the potential gradient again attained its fair weather value.

Professor Wilson pointed out that the negative potential gradients produced below a thunderstorm are sufficiently great to start, and maintain, point discharges at elevated points on the earth's surface. He also stressed the importance of these discharges in the maintenance of the earth's charge.

Since the potential gradient is, in the majority of cases, negative under a thunderstorm, the charge induced on the earth's surface must be positive, The point discharge must therefore mean the liberation of positive charges to the atmosphere. In this way the point discharge helps to maintain the negative charge on the earth.

Professor Wilson also showed that the lightning flash itself brought down to earth an average of 20 coulombs of negative charge.

Obviously therefore the investigation of point discharge currents is necessary for the explanation of the mechanism of the thunderstorm and the maintenance of the earth's negative charge.

Many observations have been made on point discharge currents in elevated platinum wire points, noteably by Wormell (2) Chalmers and Little (3) and Whipple and Scrace (4). These observations have produced many interesting results, and serve to confirm the importance of point discharge currents in the electrical exchange between earth and atmosphere. Using the data obtained from his point discharger and other relevant observations, Wormell showed that the point discharger was the biggest single contributor to an electrical exchange "balance sheet", and that the contribution made was that of 100 coulombs/sq. km. per year of negative charge at Cambridge.

Schonland in South Africa, in an attempt to use a natural point discharger, carried out experiments on a bush tree. His observations were not continuous and so no comparison can be made with the work of Wormell. However he was able to calculate that the discharge per sq. km. in a thunderstorm was at the rate of 0.18 amperes. The thunderstorm must now be considered not only as separating out the charge in the cloud itself, but also neutralising the positive charge liberated by point discharges.

The liberation of the positive charges by point discharges allows an explanation of the predominance of a nett positive charge on the shower cloud raindrops. The Wilson process of ion capture would explain this. A rain drop falling through the cloud would pick up a negative charge. As the drop falls through the base of the cloud the polarisation becomes reversed and so the negative charges appear at the base of the drop. As the drop falls to earth through the rising stream of positive ions liberated by point discharge, it loses its nett negative charge and proceeds to charge again, by the Wilson process, arriving at the ground with a nett positive charge.

Some criticism of the validity of the Wilson theory has been based on the lack of evidence of the existence of an adequate amount of ions in the atmosphere for the process to be effective. The observations with point discharges have so far been artificial in nature and even the bush tree used by

Schonland cannot be considered as a completely natural point discharger.

Measurements of the point discharge taking place in trees growing naturally, in varied sites and of varying heights, would therefore be of great value. If such observations could be made, then an accurate estimate of the true value of the natural point-discharge from the earth in the electrical exchange between the earth and atmosphere could be attained. At the same time a valuable contribution to the complete description of the complicated working of the thunderstorm would have been made.

The following research is presented as a contribution to the solution of this problem.

The Tree and the Site:

The tree chosen for this investigation was a Scots Pine. Situated in an isolated position and 53 feet in height, the tree is probably the most effective point discharger in the area. The shape of the tree, and especially of the pine needles themselves, must be assumed to give very nearly the best approach possible to the most efficient natural point discharger in the form of a tree.

The photographs overleaf show the comparative isolation and dominance of the tree.

The ground near the tree was covered with rough grass and a plantation of young pine trees, none exceeding three feet in height. Due to a slight hollow in the ground formation, in which the tree stood, the earth was generally damp or wet and must have been a good conducting medium at all times. (A small marsh area existed about 150 ft. to the N.W.).

The tree was healthy. There was no indication of any disease or fungi, although one branch had been dead for some years. Judging from the number of pine cones precipitated on to the hut and the observer the tree was indeed active !

The Tree from the South-West.

The Tree from the South-East.

The Initial Instrumental Requirements :

An estimate must be made for the magnitude of the point discharge currents expected. In the work carried out, with artificial platinum wire point dischargers and the "bush" tree used by Schonland, currents of 1-20 micro-amperes were observed. It has long been assumed, in the theoretical implications of these experiments, that the point discharge current from a tree is of the same order of magnitude as the currents in an artificial point raised to the same height. The work of Chiplonkar (6) cast some doubt on the validity of this assumption. The probable explanation for the observations of Chiplonkar is included in the report of the second experiment. As a first approximation therefore it was assumed that the point discharge currents in trees are in the range of one micro-ampere to one milli-ampere.

The choice of a tall isolated tree for this experiment is indicated for obvious electrical reasons. A tree, whose diameter at the base was just less than 1 metre, was chosen the height being 53 feet. The detection and measurement of currents in the tree of the above order of magnitude, by their magnetic effects, requires the use of a very sensitive recording magnetometer.

The magnetometer measuring device in this case cannot be placed nearer the centre of the tree trunk than a distance of 50 cms. At this distance the assumed discharge currents produce magnetic fields of the order of $10^{-8} - 10^{-5}$ oersted. The most sensitive magnetometer available today is capable of a maximum sensitivity of 10^{-6} oersted. It is therefore likely that only the discharge currents experienced in thunderstorm conditions could be measured directly.

The use of a high permeability metal, forming a magnetic circuit about the tree, can be used to "amplify" the magnetic fields to be measured. Using a mumetal girdle (1 in. diam. mumetal rod) in the shape of a square (side length :1 metre) and containing a 1 mm. gap in one side, the magnetic fields are amplified to the order of $10^{-5} - 10^{-3}$ oersted in the gap. This calculation is made on the assumption that the mumetal permeability is infinite and consequently the total Magneto-motive Force appears across the small air gap, or

$$M.M.F. = H_{gap} \times d$$
$$\therefore H_{gap} = \frac{4\pi i}{d.}$$

where H gap is the magnetic field in the gap of d cms, the discharge current being i amperes.

The measurement of this gap field may be possible in two ways. A form of alternating current generator may be devised to fit into the gap or alternatively a form of electronic magnetometer (or magnetic amplifier) may be adapted to make the maximum use of the mumetal girdle properties.

Much calculation was carried out on the possible methods of vibrating or rotating a coil assembly in a small gap to form an alternating voltage generator. These calculations indicated that, ignoring any mechanical or constructional difficulties, the output signal would be of the order of 10^{-18} - 10^{-16} watts. These figures show that the output voltages would be at the limit of sensitivity of all but the best valve amplifliers. It was therefore decided to concentrate on the alternative possibility, the adaption of an electronic magnetometer.

The modern trend in magnetometer design has been on the lines of the magnetic ampliflier. There are three distinct types, the second harmonic magnetic ampliflier, the mumetal "skin effect" a/c bridge magnetometer, and the "airborne" magnetometer. Experimental conditions and advice led to a first choice of the second type. The instrument was constructed on the lines of that described by A. Butterworth (7). This instrument has a sensitivity limit of 10^{-6} oersted. An attempt to construct an instrument of this type was made, a report of which is included in the Appendix. This attempt failed to produce an adequate sensitivity.

The next attempt to produce an adequately sensitive magnetometer, was based on the airborne magnetometer design. This instrument is generally described as the airborne magnetometer, as it was developed during the war for use in aircraft, and is now adapted for geophysical survey work. The design of the "measuring element" is simple, and easily adapted to the experimental conditions of the mumetal girdle.

The magnetometer "head" or "measuring element" used in this experiment was such that the mumetal magnetic circuit could be made complete. This fact reduced to a minimum the interference of the earth's magnetic field changes with the instrumental response.

The use of this magnetic circuit in the form of a mumetal girdle has however an unfortunate disadvantage. When not in use the incomplete magnetic circuit is liable to respond to changes in the earth's magnetic field. These changes cause a residual magnetic polarisation to be retained by the girdle. On completing the circuit by the insertion of the magnetometer head, the magnetic field "zero" or "base line" is of an indeterminate value. Some system had to be devised to enable the experimenter to vary this "zero" field so that the magnetometer worked at all times under the same magnetic bias conditions. This was achieved by the addition of a magnetic bias coil to the magnetometer head.

The instrument must be made fully recording and have a "time constant" of response consistent with the changes to be measured.

<u>The Instrument:</u>

The principles, on which the working of the airborne magnetometer depends, were gleaned from various articles in the scientific press. The entire design and adaption of the instrument to this research was carried out without further reference to the design of similar instruments.

Basically the magnetometer is a magnetic ampliflier. A mumetal wire subject to an external magnetic field, automatically becomes magnetised along its length in proportion to the component of the magnetic field in that direction. This is due to the high value of the mumetal permeability (approx. 10-20,000) after suitable heat treatment. This magnetisation will be referred to as the imposed magnetic bias. If this biased wire is subjected to a pulsed current running in a primary coil, linked with the wire, it can be made to attain saturation for the magnetic induction. The magnetometer head was designed and made to use this fact in the following manner:

A mumetal wire (26.S.W.G. 6 cms. long.) formed the core of a transformer. A small coil, or solenoid, was wound on to the thin polythene tube that ensheathed the wire. (This tube allowed the wire to be slipped out for testing or replacement). This coil is called the Bias Coil. A primary coil was wound on to the Bias coil, being coiled for half its length clockwise, the other half anticlockwise. Care was taken to ensure that the two halves were identical in every respect. A unidirectional secondary coil (or pick-up coil) was wound on top of the primary. Finally a small coil was wound on a paper cylinder and slipped over the secondary to form a moveable secondary coil for balancing purposes. This assembly formed the magnetometer head.

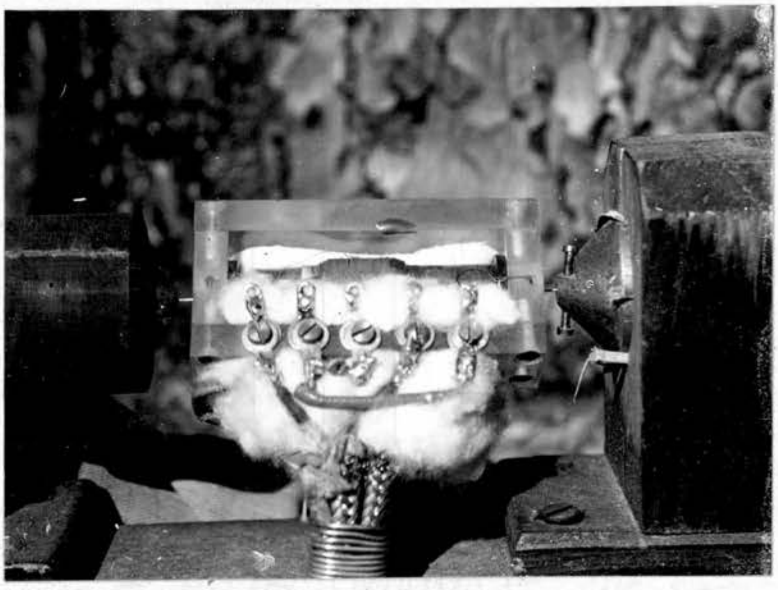
If the mumetal wire is removed, the coil assembly forms an air-cored transformer. A pulsed current passing in the primary coil causes induced voltages in the secondary coil. Due to the opposed nature of the primary coil windings, these voltages are also opposed. By coupling the short coil to one end of the secondary, a position may be found for it such that the opposed induced voltages are made equal. The secondary coil then produces no output signal. The two halves of the primary coil are equally linked with the secondary.

A similar procedure must be carried out to ensure equal linkage between the opposed halves of the primary coil and the mumetal wire core when replaced. This may be done by shunting the two halves of the coil by a potentiometer. When the wire does not experience any imposed bias (very difficult to attain) there is again no output from the secondary if the primary halves are equally linked with the mumetal core. If an output signal exists, then by suitable setting, the potentiometer can be made to remove it. The potentiometer, in this case, was found to be unnecessary.

In this balanced state and in the absence of an imposed magnetic bias, the passage of a suitable pulsed current in the primary coil causes magnetic saturation in the two halves of the mumetal core. The two halves are magnetically biased in opposite directions. The induced voltages in the secondary coil are opposed and balanced, consequently there is no output signal. This is true of both the growth and decay of the primary current pulse.

If now the mumetal core is placed in an external magnetic field, both halves of the wire become similarly biased. On the passage of the primary coil pulse, the halves of the wire saturate at different times. The time interval between the saturation of the halves, produces a momentarily unbalanced induced voltage in the secondary coil. This unbalanced voltage thus produces an output signal pulse. The peak value of this pulse is found to be proportional to the strength of the imposed magnetic field. Measurement of the peak value of the output pulse thus gives a method of measuring the relative values of external magnetic fields.

The diagrams of the magnetometer head construction and the method of working are shown overleaf.

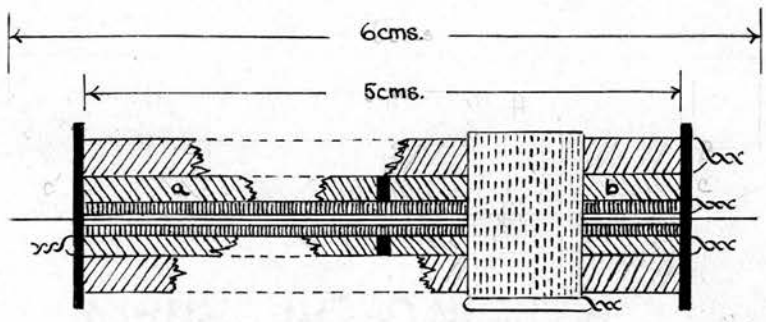


The Magnetometer Head.

This photograph shows the magnetometer head in its working position. The coil assembly is held in a Perspex frame. The ends of the mumetal wire can be clearly seen where they enter the specially drilled pole pieces of the girdle.

The length of 6 cms. was chosen for the magnetometer head wire, thereby making the reluctance of the element wire ten times that of the girdle. In this way the maximum use was made of the "amplifying' effect of the girdle.

CONSTRUCTIONAL DETAIL



BALANCING SECONDARY COIL

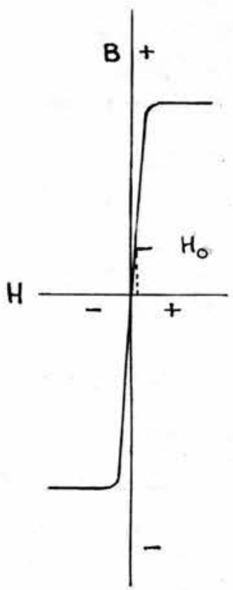
SECONDARY COIL

PRIMARY COIL a WOUND CLOCKWISE
b WOUND ANTICLOCKWISE.

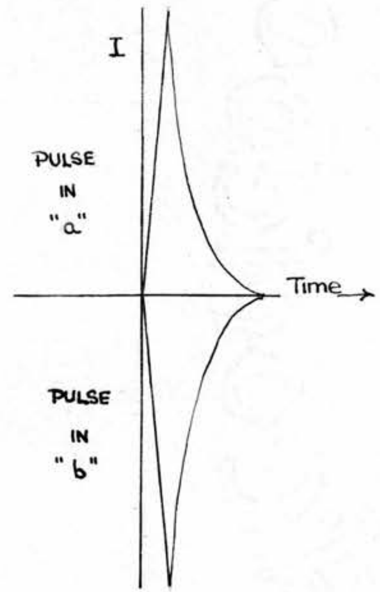
BIAS COIL

PLASTIC TUBE

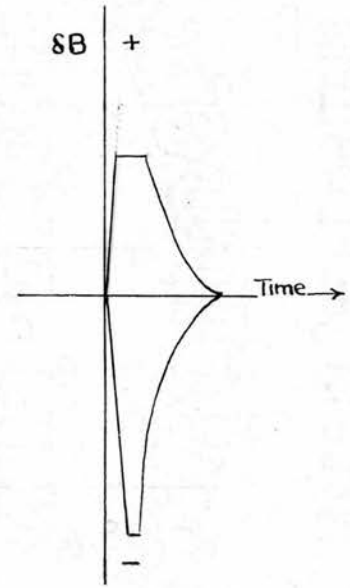
DIAGRAMS OF WORKING CYCLE IN THE MAGNETOMETER HEAD



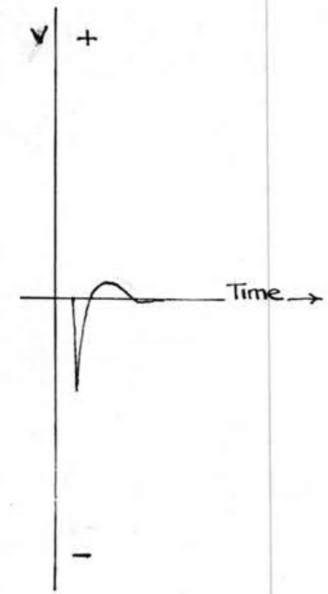
INITIAL MAGNETIC
BIAS CONDITIONS
(H_o)



PRIMARY COIL
CURRENT PULSE



CYCLE OF
MAGNETIC CHANGES
IN WIRE CORE



RESULTANT
SECONDARY COIL
OUTPUT SIGNAL

One feature of the experimental magnetometer head, was a "ringing" induced in the secondary coil by the pulsing current. Attempts to remove this signal only resulted in a reduction of signal strength. It was therefore left uncorrected. The ringing signal was found to be independent of the magnetic pulse signal. As only the magnetic pulse peak is passed into the latter stages of the amplifier section, this spurious signal did not affect the recorded output.

The first, or Bias coil, usually carries a D.C. current of 1 - 10 mA. This current thus creates an artificially induced magnetic bias on the wire. This bias is used to counteract any changes in the magnitude of the original imposed magnetic bias between recordings. Being variable the current can always be set so as to produce the same initial output signal. This variation allows the coil assembly and the valves to work each time under the same conditions, thus ensuring the same amplifier response.

The amplifier section of the instrument is normal in construction. The input signal is passed through three stages of straight amplification. The third stage is given a variable bias voltage of + 70 volts on the cathode. This arrangement allows sufficient amplification of the input signal, before the third valve cathode bias suppresses all but the signal peak. The pulse peak is now inverted, amplified and again inverted before being passed to a valve volt meter. The valve voltmeter stage works both as a leaky grid detector and a peak voltmeter. This combination is found to be necessary to attain the stability of the rectified current required for recording.

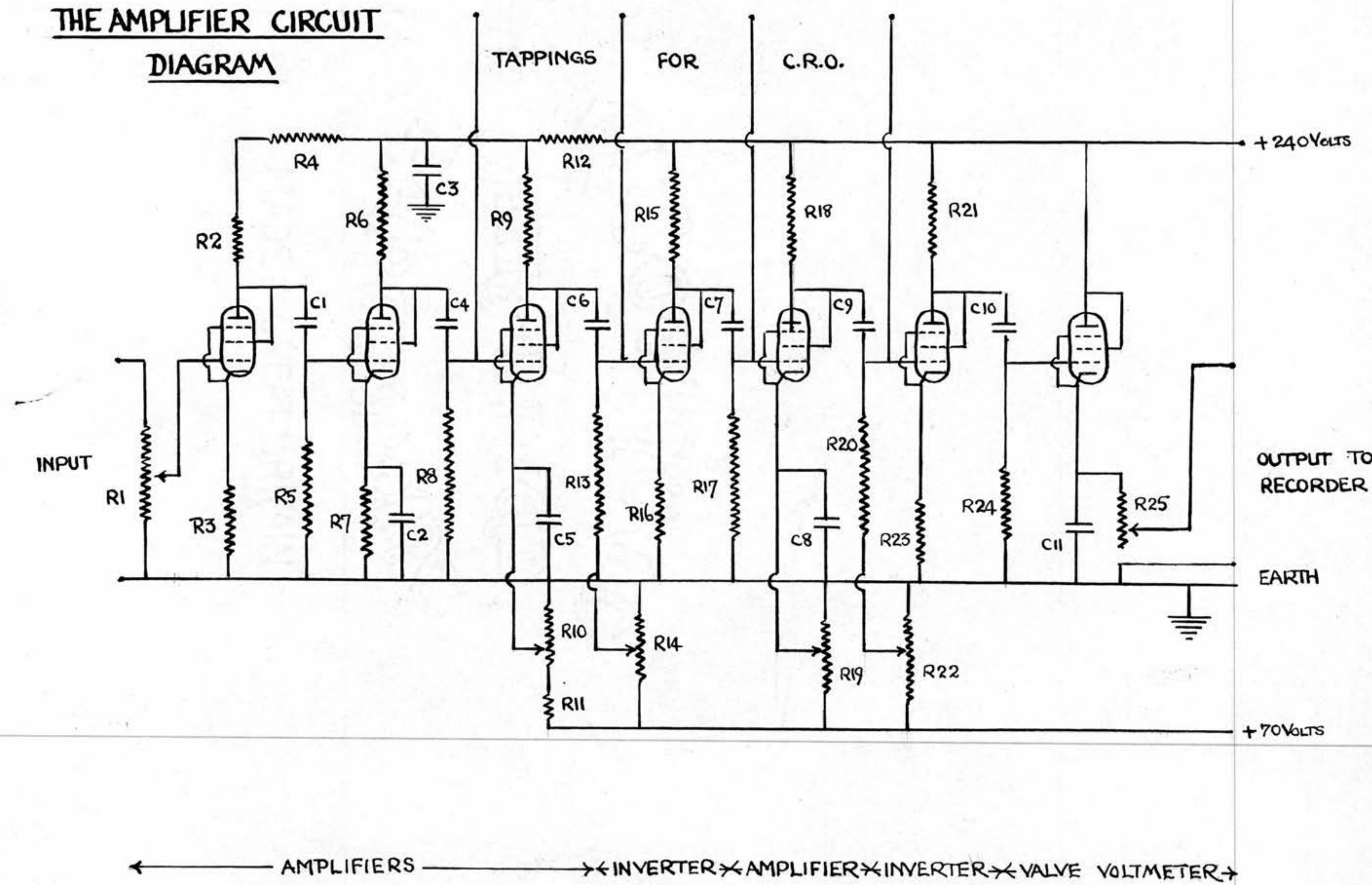
The output of the valve voltmeter is passed through a milliammeter and an Esterline-Angus pen recorder (0 - 2 mA.D.C.) placed in the cathode lead. The recorder is only switched in after the instrument has been set working under its normal conditions.

The pulsed current required for the primary coil, is drawn from a multivibrator. The coil is placed between one of the grid leak resisters and "earth". The required magnitude, wave shape, and repetition frequency of the pulse is attained by suitable choice of components.

The instrument is connected up in the following manner. The girdle is set permanently about the tree and kept in position by a wooden trestle construction embedded in stones to give rigidity. The gap in the magnetic circuit is first closed by placing the magnetometer head in the gap. The mumetal wire ends are inserted into the specially drilled pole pieces. One of the girdle rods is slid along until the wire is firmly held in position,without pressure or bending and shows no lateral or horizontal movement in the gap. The wires to the oscillator, amplifier, and power supplies are then connected. The instrument is then allowed five or ten minutes to warm up.

A battery powered G.E.C. Miniscope is used to investigate the signal pulse wave form at the grid of the third valve. Suitable variation of the Bias coil current allows this wave form to be changed until it is only slightly larger than its minimum value. This procedure ensures that the mumetal wire is affected by an almost zero magnetic field. The working conditions of the magnetometer head and the valves are now standard. Investigation,by C.R.O., at the grids of the remaining valves, ensures that they are working properly and that the bias conditions are correct. Finally the input potentiometer is varied until a suitable magnitude of output signal sensitivity is attained. The recording instrument is then switched into the circuit.

THE AMPLIFIER CIRCUIT DIAGRAM

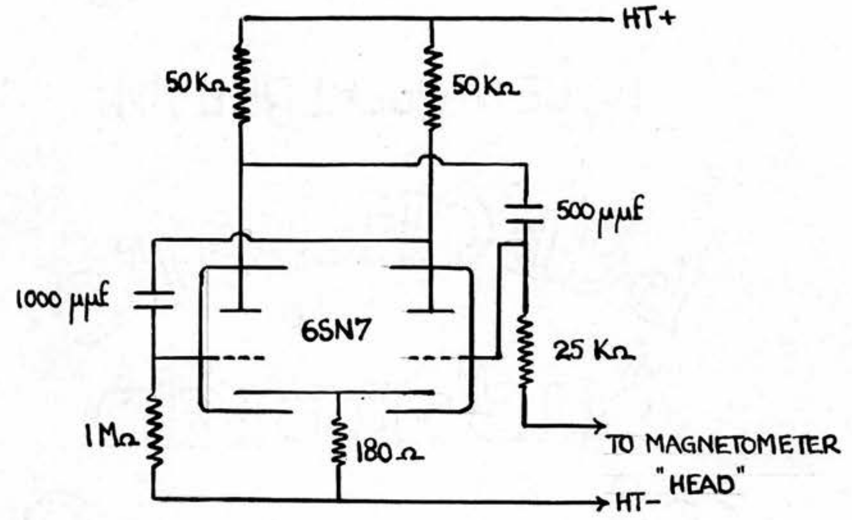


List of Amplifier Components:

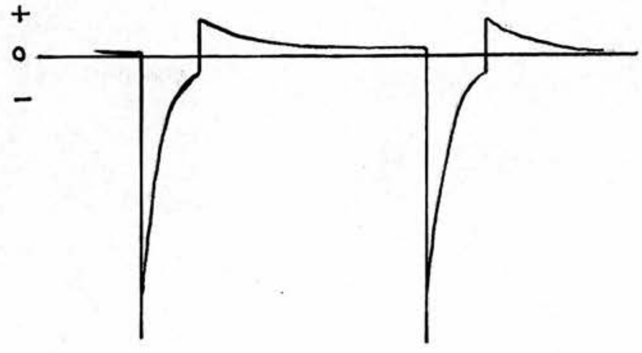
Resistances (ohms)		Condensers (farads)	
R 1	1 Megohm	C 1	1000 uuF
R 2	100,000	C 2	25 uF
R 3	2,000	C 3	4 uF
R 4	10,000	C 4	1000 uuF
R 5	1 Megohm	C 5	4 uF
R 6	10,000	C 6	1000 uuF
R 7	180	C 7	1000 uuF
R 8	1 Megohm	C 8	4 uF
R 9	100,000	C 9	1000 uuF
R10	100,000	C10	4 uF
R11	100,000	C11	500 uF
R12	10,000		
R13	2 Megohm		
R14	100,000		
R15	50,000		
R16	10,000		
R17	2 Megohm		
R18	10,000		
R19	1 Megohm		
R20	1 Megohm		
R21	10,000		
R22	1 Megohm		
R23	6,000		
R24	500,000		
R25	1,000		

All valves are 8D3 miniatures. B7G base.

THE MULTIVIBRATOR CIRCUIT



WAVE FORM



The Girdle.

This photograph shows the girdle in its position around the tree. The magnetometer head can be seen to be held in position by the girdle pole pieces and a clamp.

The Amplifier and Recording Apparatus.

This photograph shows the layout of the apparatus in the hut when the instrument was working.

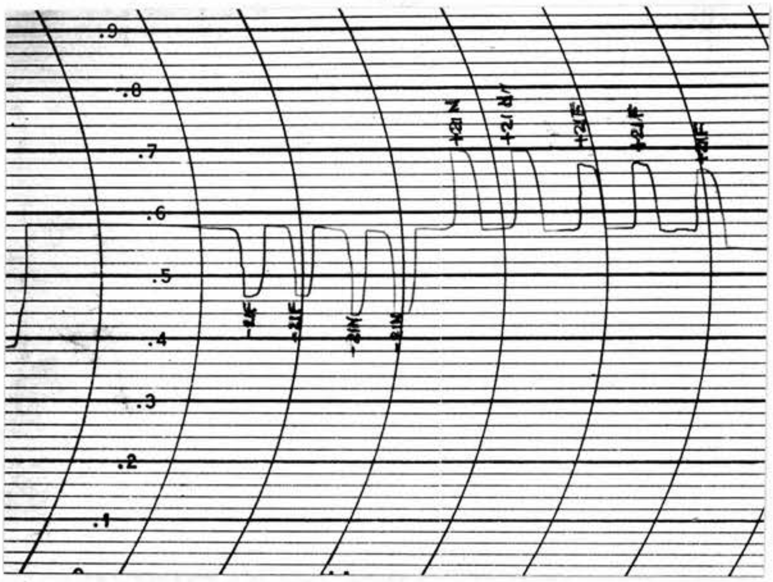
1. The Multivibrator.
2. The Amplifier.
3. The Ammeter (in the cathode lead of valve voltmeter.)
4. The Miniscope.
5. The Esterline-Angus Recorder.
6. The Bias coil D.C. current control.
7. The Recorder switch and control.

Possible Sources of Error :

The calibration of the recorded trace became in practice a continuous process. During all periods of recording, a known current (21 milliamps) was intermittently passed up or down a wire attached to the tree and linked with the girdle. This wire was placed as far from the magnetometer head as possible. The current, although passing in a wire, produced a megnetic field in the same way as the discharge current in the tree. The magnetic field of this current was thus superimposed on that already present and due to the discharge current. The recorded trace therefore showed a "pip" that coincided with the running of this test current. The sensitivity of the instrument could thus be immediately determined during the actual running of the experiment, by the application of a series of "test pips", spaced at reasonable intervals along the trace itself. No reference to the actual value of the magnetic field strength was therefore necessary. The calibration "pips" gave a deflection of so many millimetres for a test current of one milliampere. This "test pip" also indicated whether the change in discharge current was an increase or a decrease of the current running up the tree.

The question arises as to whether the girdle was in fact an efficient magnetic circuit. If the girdle was efficient then the positioning of the test wire was not of importance. Similarly the changes in the earth's magnetic field would not have affected the recordings. The efficiency of the girdle was tested in the following manner. The test wire was first placed 10 cms. distant from the magnetometer head. A test current of 21 milliamps was passed through it when the instrument was recording. This test was repeated. The wire was then moved until 100 cms. distant from the magnetometer head and the test current passed again. In the absence of the girdle the ratio of the recorded test "pips" would have been 10:1. With a girdle, 100% efficient, the ratio would have been 1:1. As shown on the accompanying photograph of this test, the ratio is approximately $6\frac{1}{2} : 5\frac{1}{2}$. Thus it can be concluded that the girdle is approximately 85% efficient. The test wire was finally fixed at the 100 cms. distant position.

The result of this test showed that some part of the magnetic flux, due to the test wire, escaped from the magnetic circuit. The earth's magnetic field consequently can be presumed to have affected the circuit to a slight extent. Changes in the earth's field therefore must also have affected the circuit, appearing on the recorded trace in the same way as a change in the discharge current.



The Girdle Efficiency Test.

This photograph shows the result of the girdle efficiency test. The "test pips" are shown for currents of 21 milliamps passed up and down the test wire, when placed 10 and 100 cms. from the magnetometer head.

+ 21 N	21 mA passed up the wire, 10 cms. from magnetometer head.
- 21 N	21 mA passed down the wire, 10 cms. from magnetometer head.
+ 21 F	21 mA passed up the wire, 100 cms. from magnetometer head.
- 21 F	21 mA passed down the wire, 100 cms. from the magnetometer head.

Note how the recorded trace returns to its original position after the "test pip" deflection.

During recordings this fact became very evident. On occasions magnetic storms became so violent as to render the instrument useless. This disadvantage of the girdle made it necessary to ensure that recordings of the discharge currents were only taken when additional changes of magnetic field, due to the earth's field changes, were not present. The method employed to avoid such errors, was to extract recordings from the trace produced over as short a period as possible. All observations that showed any variations that did not coincide with the cloud cover were discarded. Any trace that did not return, after the passage of a cloud, to its original base line or zero was also discarded.

In some of the traces included in the results the base line has changed by a large amount. These cases have been "normalised" by the assumption of a steady rate of change of the imposed magnetic field. The justification for the inclusion of these results was based on the fact that the recorded trace showed decisively that the steady rate of change had been established before the record of the cloud passage and had continued unchanged afterwards. In one or two of these cases, the slow change was traced to a slow failure of the H.T. battery voltages.

The greatest disadvantage of the instrument was the absence of a definite base line or zero.

All that could be measured by this instrument was a change of the magnetic field bias. Only under conditions of cloudless skies and in the absence of magnetic storms, could it be assumed that no discharge current was running in the tree, and a definite zero obtained for the record. Conditions such as these were the exception rather than the rule and so it is only claimed that the instrument has indicated the actual change in the discharge current taking place on the passage of a shower cloud.

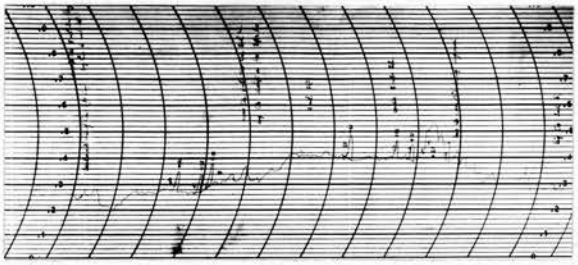
With the above restrictions on the choice of records, and the presence of the calibration "pips" on the actual trace, it is certain that no large error can be present in the results quoted. The only error capable of being estimated is that of the measurement of the traces themselves. The method used to determine the time-point discharge current graph was as follows :

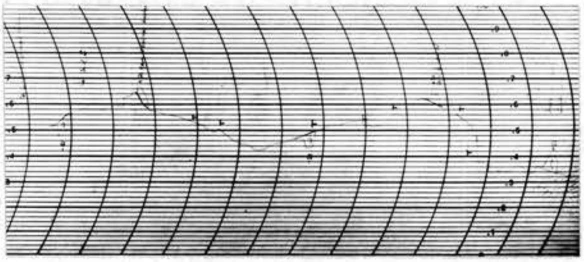
The pen recording was measured for change in current over the 225 sec. interval of the vertical line spacing of the chart. The sensitivity of the recording is established (as mm/ mA.) from the nearest calibration "pip". The difference in the levels of the trace, where it crosses the vertical time-mark lines on the chart, was measured and converted into milliamperes change in current. This

This procedure was carried out over successive time intervals and the results plotted as a graph. The graphs presented here appear as "smoothed" versions of the original trace. Each graph consists of 20-40 points obtained in this manner. The reading error is therefore very small, certainly less than 5%.

The factors involved in the experiment however are such as to make an accurate measurement of the discharge current pointless. Each tree must discharge according to its own unique shape and exposure to the earth's electric field. The absence of measurements of the electric field associated with the discharge currents further reduces the value of accurate measurement. The working of the instrument required the full time occupation of the observer and consequently simultaneous observations of the electric field were unobtainable, no automatic instrument being available.

In view of these variable and indeterminate factors, the results presented are intended to be taken only as a measure of the order of magnitude of the point discharge currents in trees. This order of magnitude will however be seen to be greatly in excess of that originally expected.





<u>Photographs of the actual recorded trace</u>.

These photographs show examples of the actual trace recorded. The "test pips" can be seen clearly. The quality of the reproduction is poor due to the fact that the violet ink of the trace did not photograph well in the absence of the correct filter.

Results:

A Table of results, with associated graphs and notes, is included in this section. The interpretation of the various columns may require some explanation.

First let it be assumed that the degree of electrical development (or total activity) of any cloud is proportional to the maximum electric field strength existing under the cloud. The maximum potential gradient must correspond with the maximum discharge current, if the conductivity of the air is assumed to be a constant. The degree of electrical activity of the cloud may therefore be associated with the maximum discharge current measured.

The total amount of charge liberated by the tree is dependent on the electrical activity of the cloud and the speed at which it passes over. In the ideal case the electric potential gradient at the earth will follow a definite cycle as the cloud passes over. Initially the fair weather positive potential gradient exists but on the passage of an active cloud this field is reversed to give negative values only returning to the initial value after the the cloud has moved away. The potential gradient-time curve must be unique for each cloud. It may be assumed, however, that an average curve does exist and that it approximates closely with that produced by the ideal distribution of charge in the polarised cloud.

If it be assumed that the potential gradient-time curve follows closely that of the ideal case, then the discharge current-time curve must follow an identical profile. The integral of the discharge current-time curve will give the total amount of charge liberated by the tree. The total charge liberated will thus be dependent on the time required for the passage of the cloud. The average value of the discharge current will however be independent of the time factor.

If the observations are arranged in the order of the maximum discharge currents measured, then it can safely be assumed that the average currents, obtained by calculation, will follow the same order. The calculated average discharge current is included in the Table of results.

Reasonable variations from the ideal discharge current-time profile, may also be taken as satisfying this assumption, provided no great change of the relative values or positions of the charge centres take place during the passage of the cloud. All the observations quoted are considered to conform with this condition.

If the results quoted were in fact affected by some external effects - such as the possible inclusion of a change in the earth's magnetic field in the readings - then they would not normally conform to the proportionality of the maximum current and the average current. The last two columns of the Table may therefore be regarded as a confirmation of the genuineness of the effect and the observations.

Mention may be made here of one or two interesting observations not included in the Table of Results.

It will be noted that in none of the observations has a measurement been made of a negative point discharge current, that is, measurement of a negative current running up the tree. (Note: The sign convention used in this work may not be the same as that used by others. A positive point discharge is considered to take place when positive charges travel up the tree. This only happens when a negative potential gradient exists due to a negatively charged cloud base overhead, the earth being considered as at zero potential. This convention was chosen as its wording gives immediately the sign of the induced charge on the point and the sign of the charge liberated to the air.)

Negative point discharge currents did take place. As only clouds with clear cut edges, that could be noted as they passed over the tree, were those of the cumulus and cumulo-nimbus type, the results quoted are restricted to these two cloud types. In all cases they gave positive point discharges.

Two cases of cloud causing negative point discharge currents are worthy of mention. Both cases occurred with the passage of a thick dark line of cloud of stable Nimbo-stratus and thick Alto-stratus, very reminiscent of old weak cold fronts. One case gave a negative discharge current of 50-80 mA, but due to the incredulity of the observer the recording was partially destroyed by interruptions of the trace to ensure that the instrument was working properly. Coincident with the clearing up of the cloud the trace returned to its original base line. The effect must therefore have been genuine.

The arrival of rain from a shower cloud was forecast by the observer on a few occasions due to a small drop in the discharge current, about 20 - 30 seconds before the rain reached the ground. The observer being inside the hut could not see the rain until it reached the ground. The original value of the discharge current would be regained within one minute. This current drop could be due to the space charge brought down near the tree by the raindrops.

The effect of the wind was quite marked. Strong gusty winds made the trace rise and fall much in the manner of a Dines anemoygraph. Each maximum of the discharge current coincided with the onset of the maximum wind velocity of a gust. Variations of ± 20 mA were recorded in gale conditions. This effect may be attributed to the more rapid removal by the gusts of an accumulated space charge, just above the tree, thus allowing a faster discharge to take place.

An aircraft, a Dakota, flying at approximately 2000-2500 feet passed directly over the tree on one occasion. This aircraft had been seen to emerge from the dark base of a thunderstorm just a minute or so beforehand. As the aircraft passed overhead, the trace dipped rapidly and equally rapidly regained its former position. The discharge current change was negative, indicating that the aircraft itself must have been highly positively charged. Due to the long time constant of the instrument, about 1 minute, the change indicated on the trace can only have been a fraction of that which actually took place. This incident, however, gave the observer great confidence in the actual working of the magnetometer.

Throughout the summer of 1951, only nine thunderstorms took place within a 5 mile radius of the tree. Only two of these passed directly overhead, both at night and before the instrument was working properly.

The following notes are short accounts of the weather conditions associated with the various graphs.

<u>18th June 1951</u>:

Wind: Westerly.
Clouds: Occasional shower Cu with otherwise broken medium Cu.

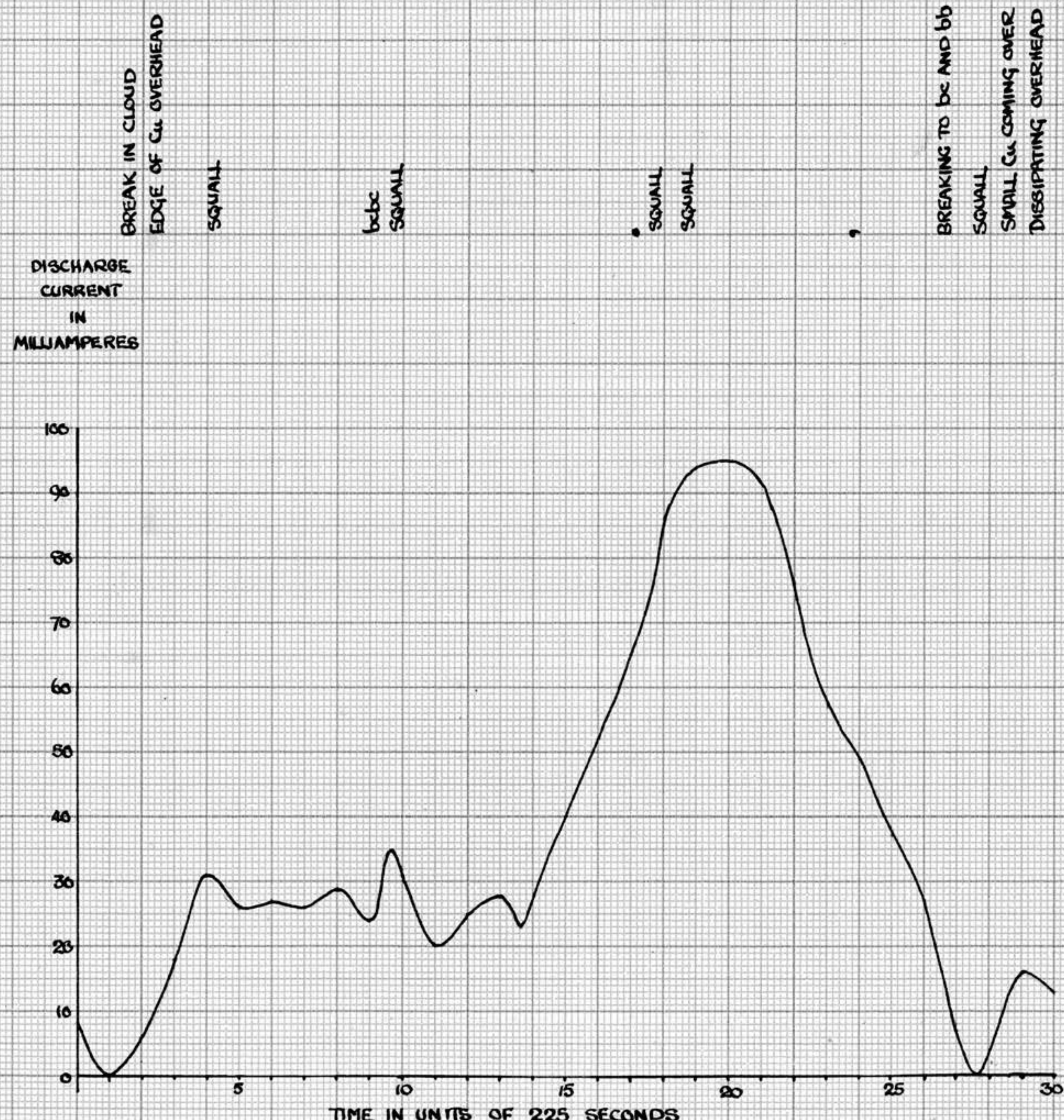
This graph indicates the passage of a large cumulus, the centre of which passed to the south of tree, followed by a larger Cu that passed overhead and was accompanied by slight rain and drizzle.

The first cloud centre passed to the south, but at the edges subsidiary connection cells formed cloud of base 3000', tops 12-14000' that passed overhead. The variations of discharge current agreed with the alternating cloud and semi-clear patches.

The second cloud as it advanced looked a really active Cu and Cb. On its passage over the tree however the cloud base disintegrated and the main cloud dissipated leaving only As and Ns with streaks of rain falling from it.

These clouds were followed by scattered small cumulus.

18TH JUNE 1951



<u>25th June</u>:

Wind: Northerly.
Clouds: Scattered thunderstorms and heavy showers.

The first thunderstorm cloud on the graph passed, at its nearest approach, about 3-4 miles to the east of the tree. The dimensions of the storm being approximably that of a cylinder $2\frac{1}{2}$ miles in radius and extending to high cirrus levels. At the beginning of the record the edge of the cirrus cloud was already overhead at the site. Coincident with the first rise in the discharge current the cloud thickened to medium height As and later lowered to give slight drizzle at the tree. The thunder was heard and marked on the trace but due to the heavy precipitation towards the centre of the cloud the flashes could not be seen. It was obvious that the cloud was in fact a double thunderstorm, the two centres being within the one cloud.

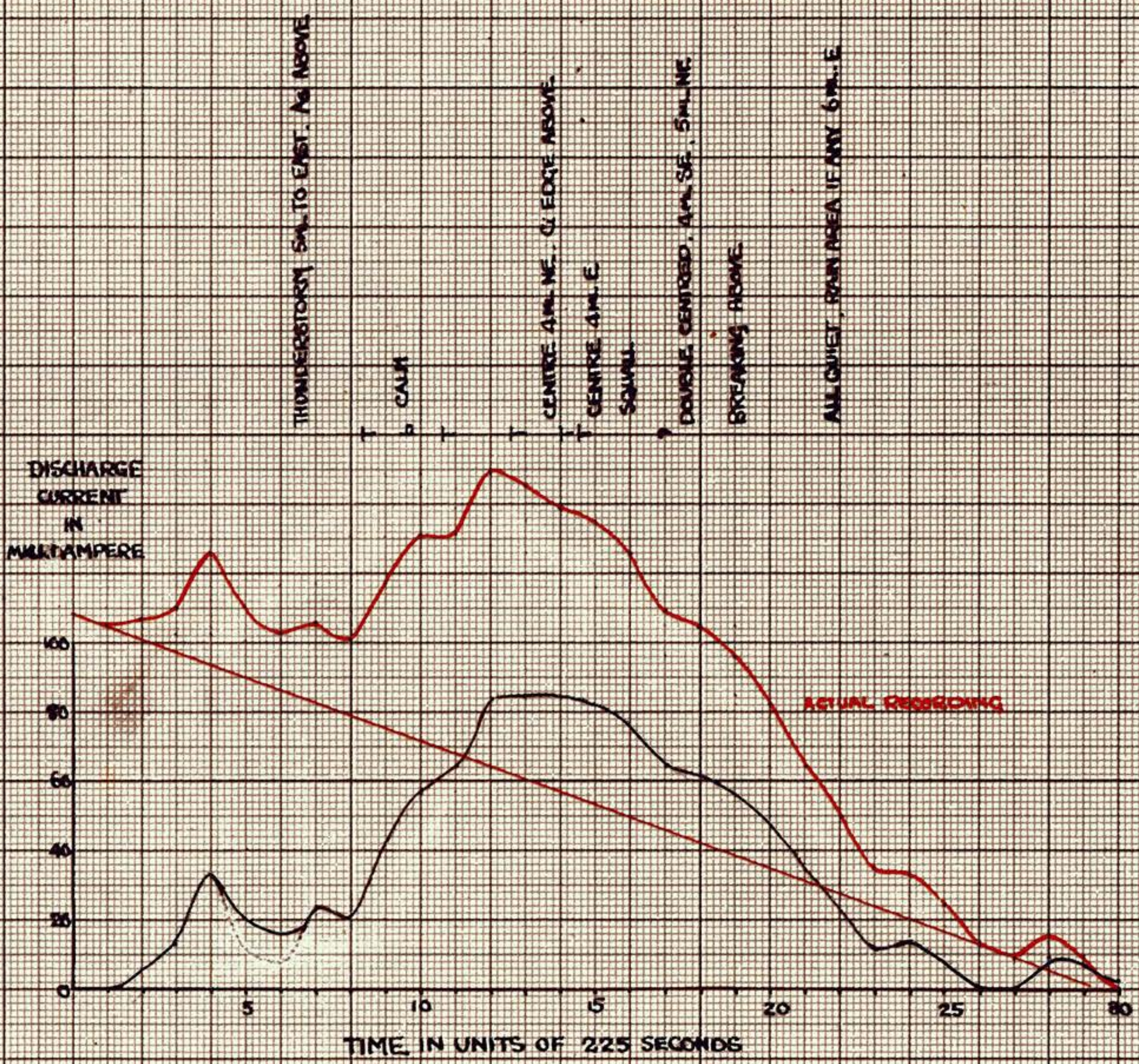
As the cloud moved off to the south the activity decreased and the graph shows a corresponding fall in discharge current, the cloud overhead thinned and cleared to AsAc.

This thunderstorm was soon followed by a heavy shower, and two less severe showers.

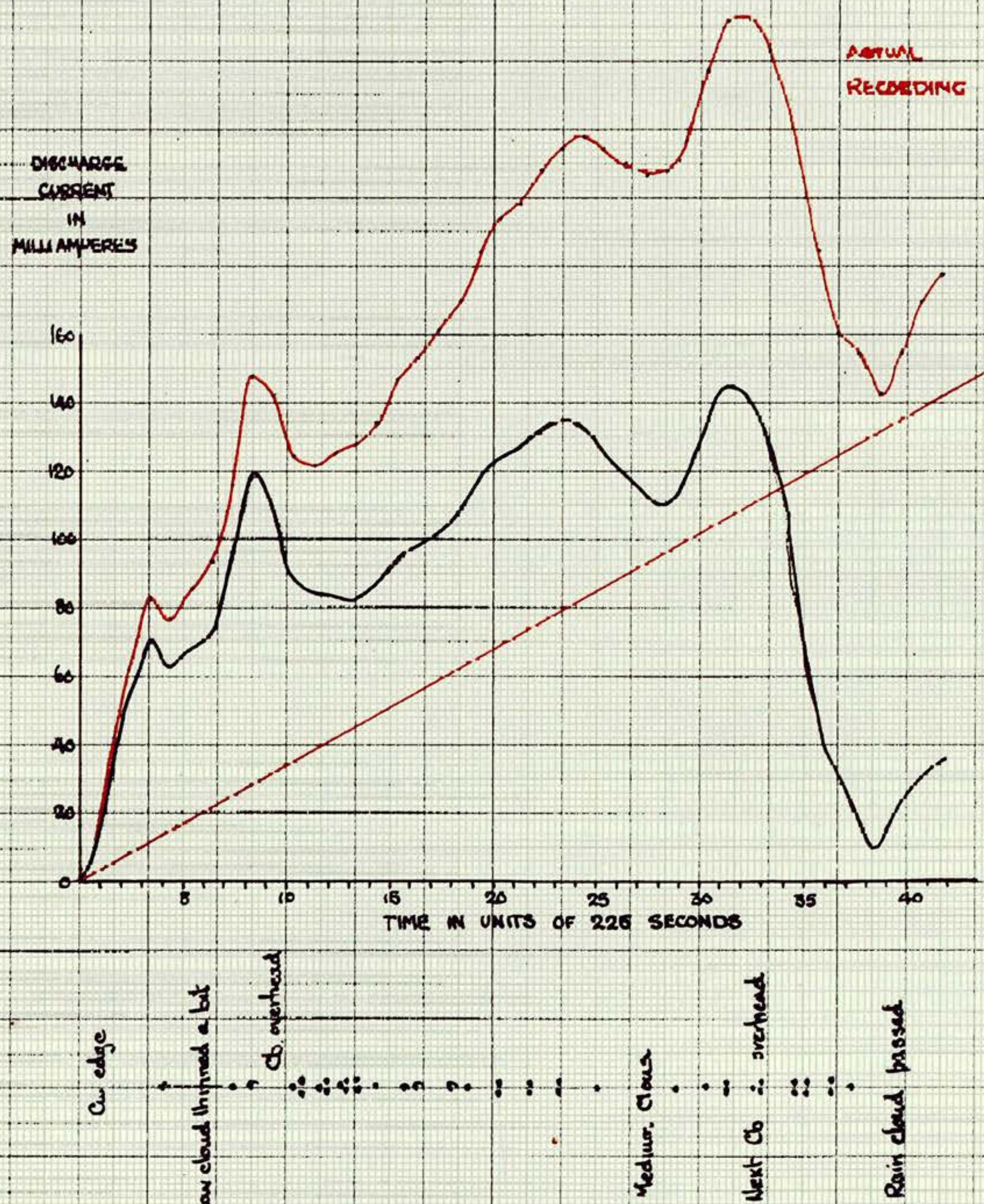
The second graph shows the passage of these showers.

These three clouds were in fact so close together that they might easily have passed as one. Although not attaining thunderstorm activity, the showers were heavy and the tops of the cloud reached the cirrus levels. It should be noted that the times of the heaviest precipitation correspond closely with the discharge maxima.

25TH JUNE 1951



25TH JUNE 1951



27th June:

Wind: Easterly or light variable.
Cloud: Layer of Sc. ending in a line of thick Ns, indicating a weak front. No low cloud after passage of front.

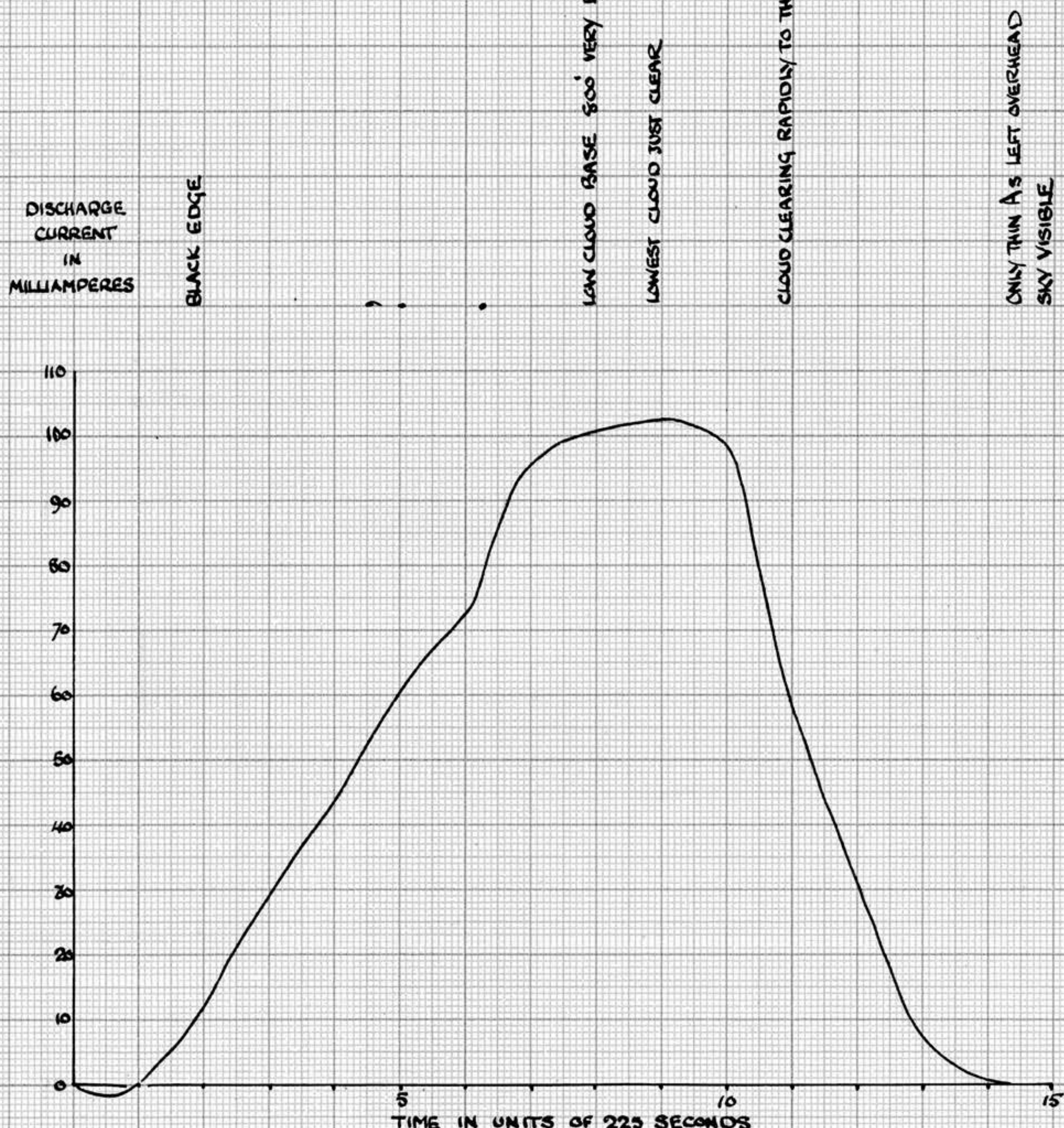
This cloud appeared on a day when only Sc. base 3000', tops 4-5000', lay in a fairly uniform sheet over the area. It was noticed that the cloud layer broke at a sharp line, running north and south, a few miles to the east of the tree.

This line slowly approached the site, darkening and thickening as it did so. On passing over the tree, slight precipitation took place, the cloud base darkening to black and falling to approximately 800 feet, with patches lower on the hills to the north.

The wind was calm and the air seemed particularly stable. As the cloud cleared all the low cloud dissipated and the base rose continuously until it formed a layer of thin As.

The whole effect was that of the passage of an old weak, slow moving, cold occlusion. No cloud could be seen to the east.

27TH JUNE 1951



<u>10th July :</u>

Wind: W. to S.W. Force 2.
Cloud: Scattered large Cu forming into thunderstorms in the evening (5 - 8 p.m.).

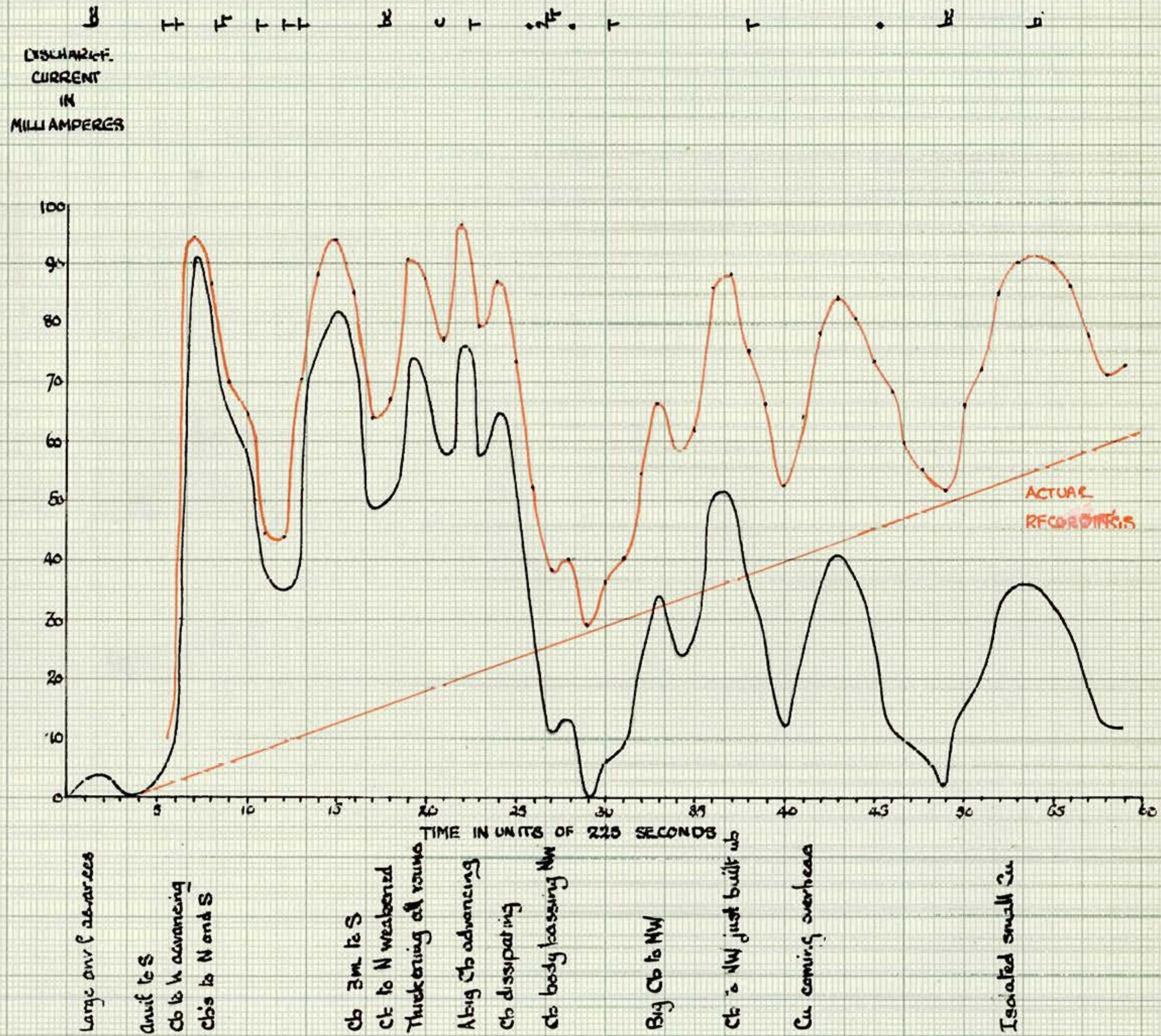
On this occasion the cumulus cloud started a rapid and violent connection over the hills in the early evening.

The tree in this case became sandwiched between two lines of thunderstorms and heavy showers. Although only scattered bits of Cu and AcAs cloud passed overhead, the thunderstorms and showers to N. and S. caused a large discharge current in the tree.

Both lines of Cb formed Ci cloud aloft that almost met over the tree. The line of Cb to the north, being the most active and persistent was mainly responsible for the slight precipitation recorded.

The last big cloud to form passed over the tree giving slight precipitation.

10TH JULY 1951

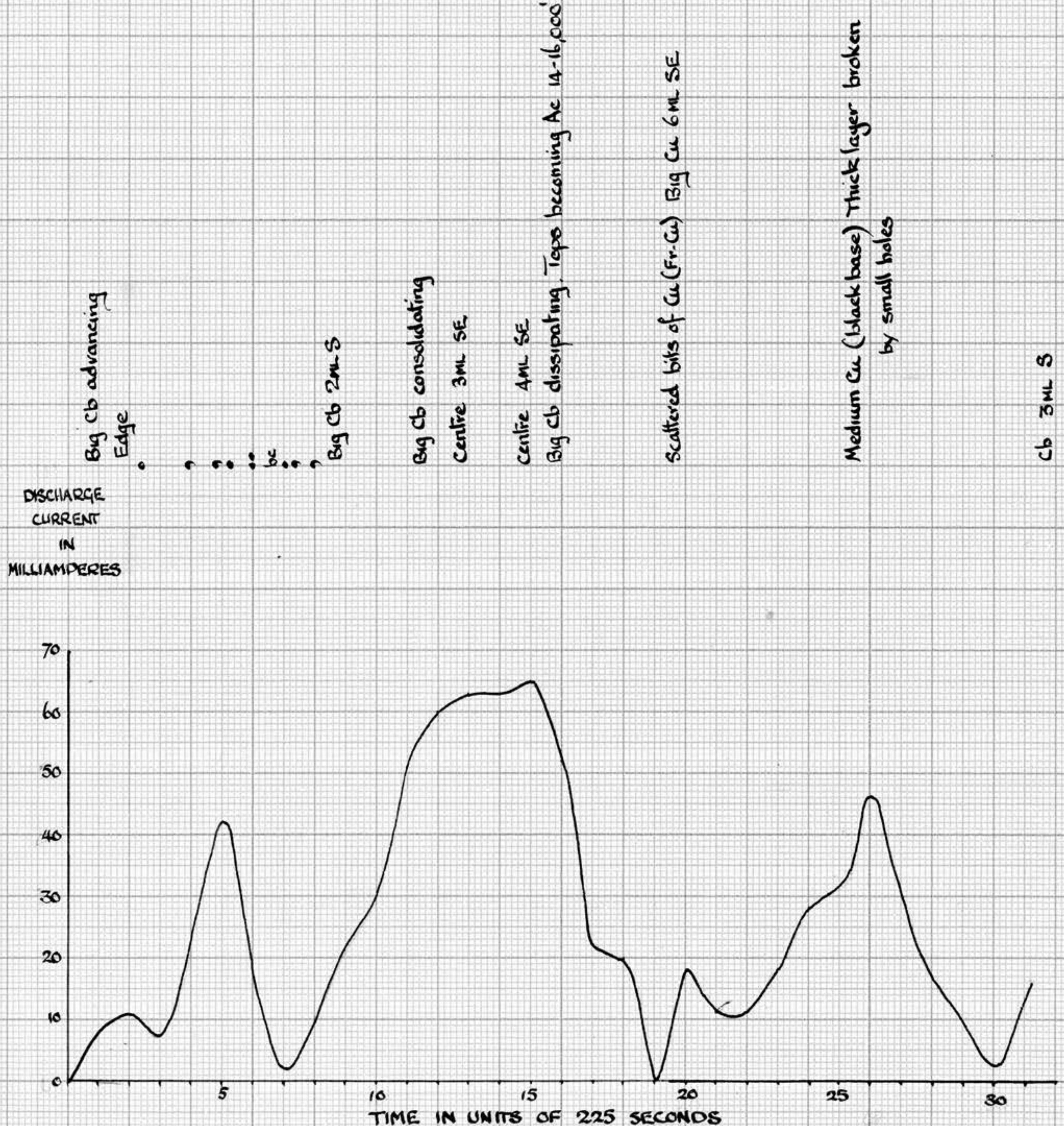


<u>20th August:</u>

Wind: W.-SW. Force 3 - 4.
Cloud: Scattered shower cumulus.

This graph shows the passage of a medium shower cloud over the tree followed by the growth of a large shower to the south. After the passage of the first shower a large Cb was seen 2 miles to the south. The approach of this cloud was rather slow and an obvious development into a thunderstorm was taking place. After the passage of the Cb to the SE., the tops were seen to form cirrus cloud. This cirrus dissipated quite rapidly and the cloud top formed into a fringe of Ac. at 14-16000 feet. The other shower clouds in the area also dissipated about the same time. The cloud that passed overhead had already subsided to form a layer of thick cumulus, in which no vertical development was taking place.

20TH AUG. 1951



27th August:

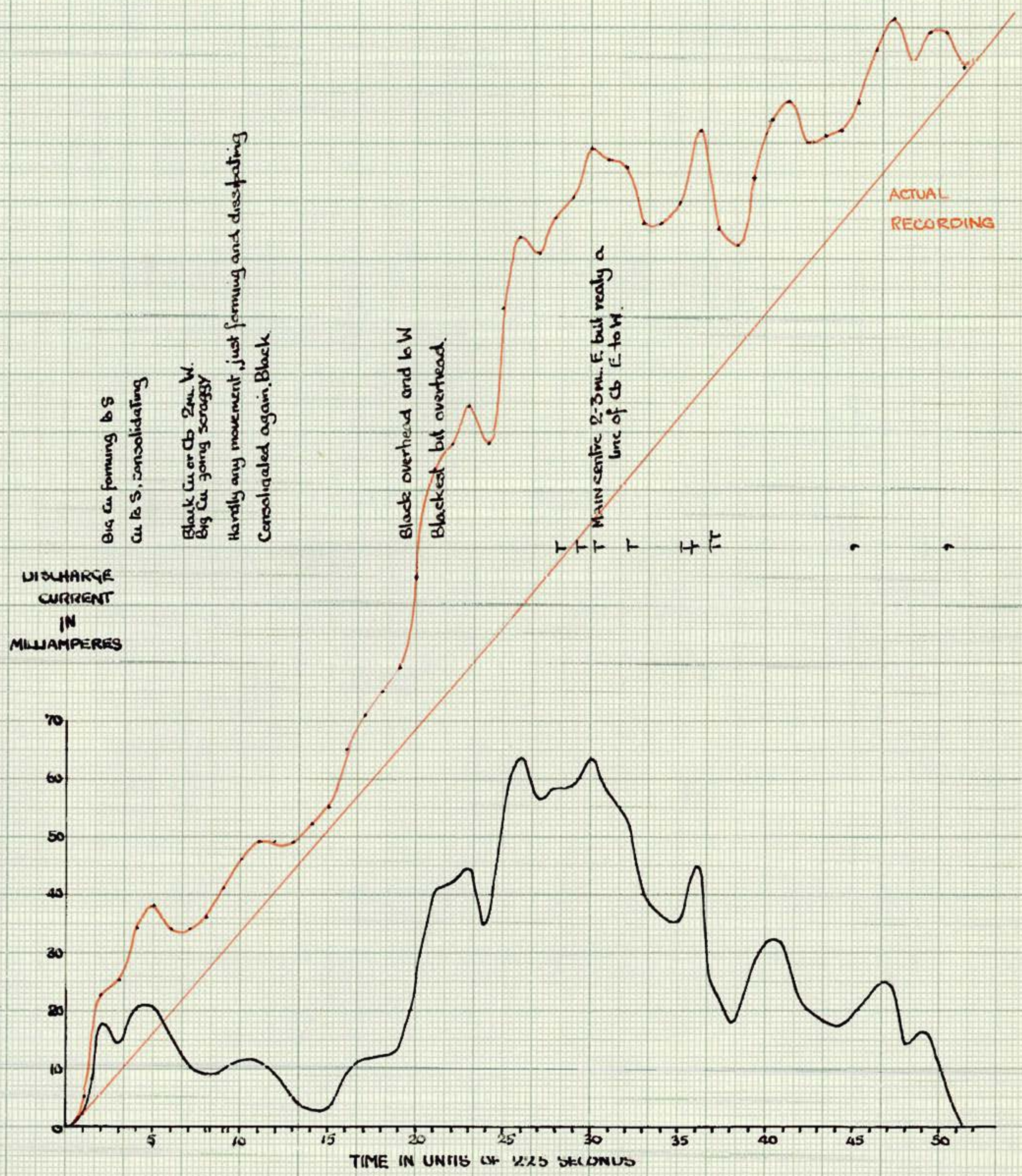
Wind: SW. Force 2-3.
Cloud: Isolated thunderstorms. Large cumulus cloud alternately dissipating and reforming.

This graph shows much the same as the previous one, only in this case the shower cloud did develop into a thunderstorm after passing to the east of the tree.

The whole development of the thunderstorm is shown. In this case the forming, dissipation and reforming of the cloud was most marked. This process of rapid development and dissipation of the cloud kept the observer in doubt as to what was really happening. The cloud itself however moved past even slower than those of the 20th Aug.

During the time the thunder was heard it was observed that the field changes, that must have been taking place, did not materially affect the recorded trace. This must have been due to the long time constant of the instrumental response.

27^{TH} AUG. 1951



31st August:

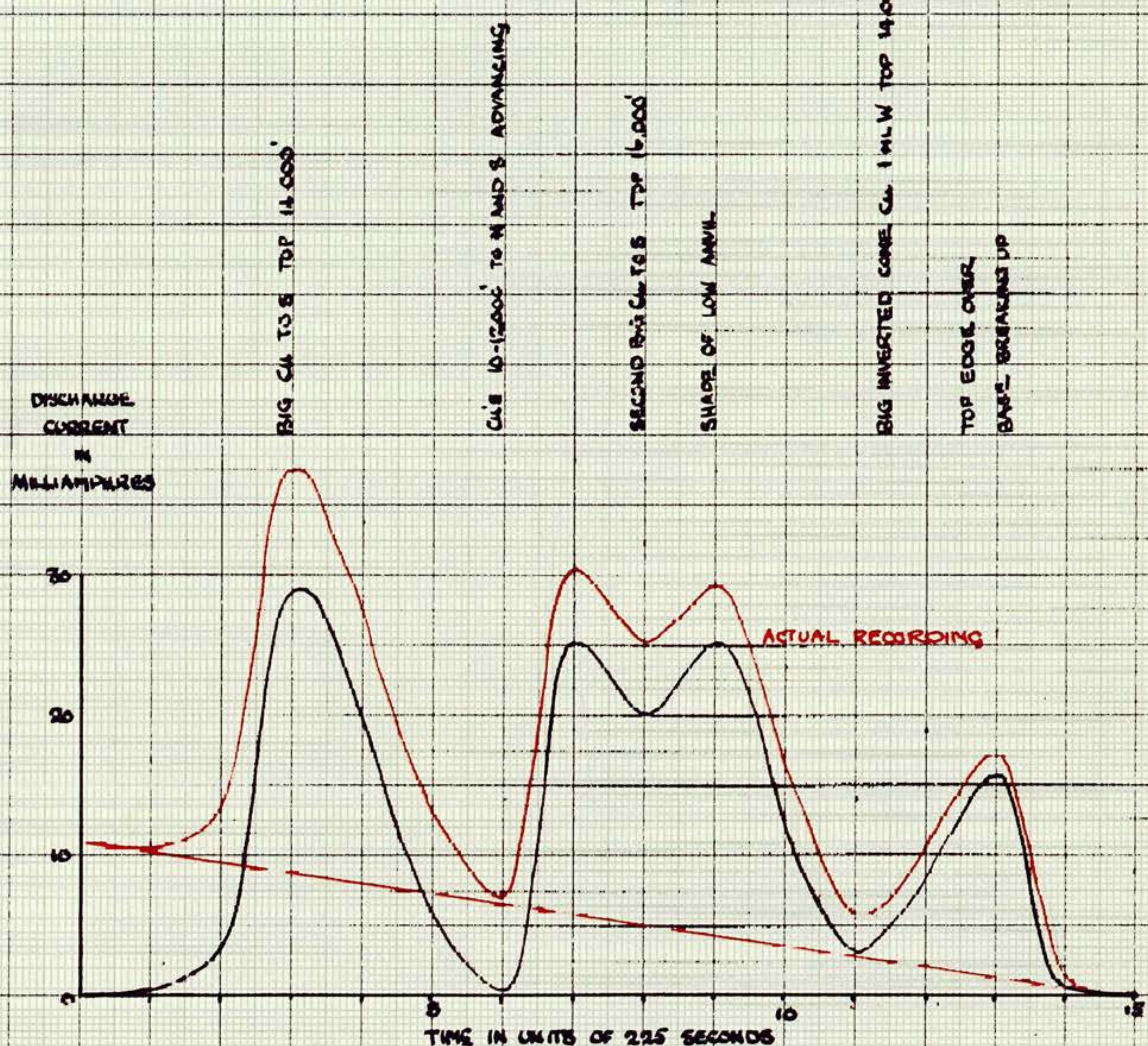
Wind: W. Force 2-3. Gusts occasionally 4-5.
Cloud: 6/10 Cu, Base 2500-3000' Tops. 5000-7000', forming into fairly general showers with a layer of cirrus stratus above.

The first two graphs show the passage of morning showers. The mid-morning showers, being small, did not produce any precipitation. The second graph shows the passage of heavy showers about one o'clock. The second shower passed over the tree giving a very heavy discharge current. Both these graphs have had to be normalised due to a steady change of the "zero" field or base line.

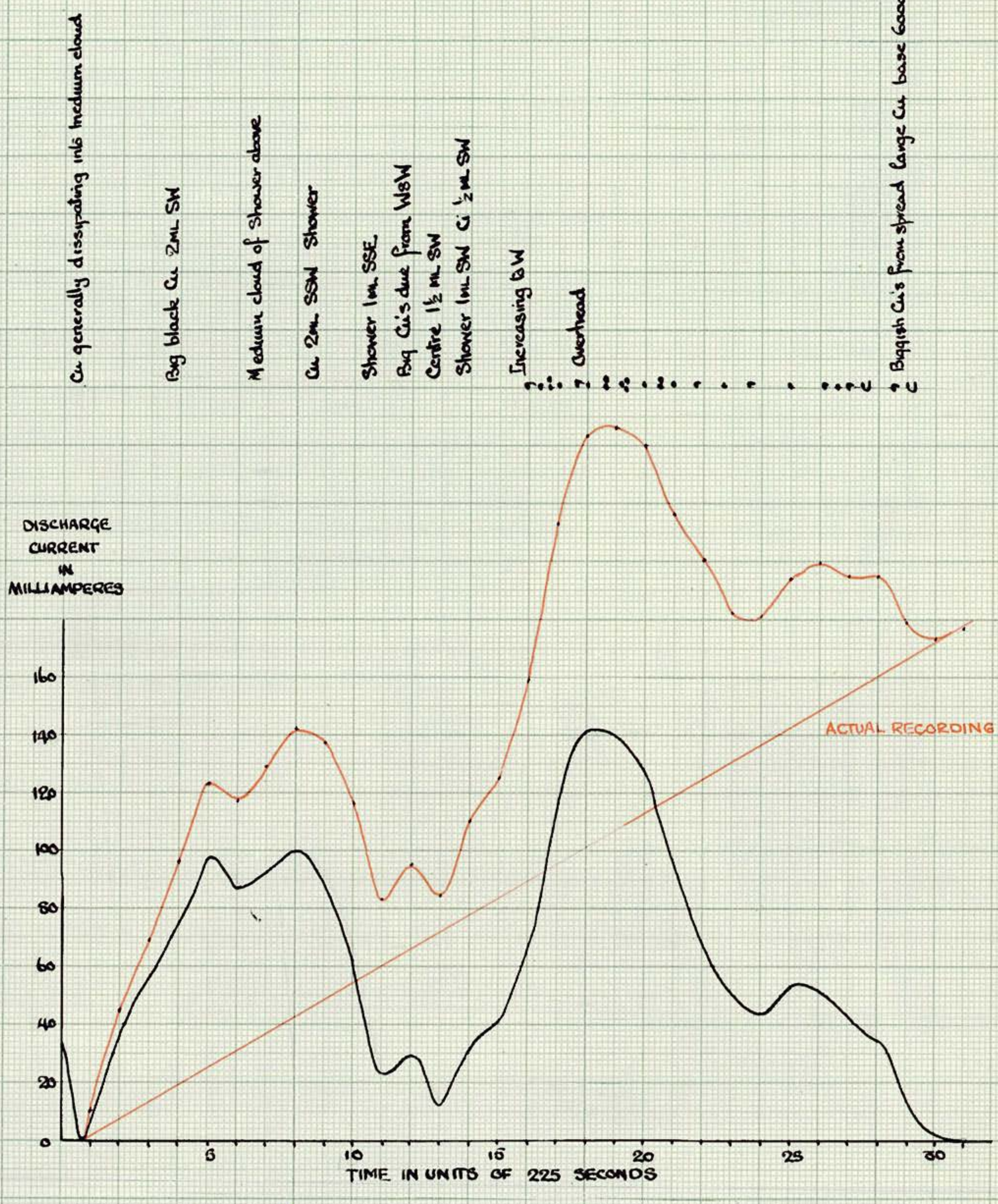
The third graph shows the passage of light showers in the evening. The sky at this time was much confused with scattered showers and broken cloud. Both these clouds passed overhead. The graph does not return to zero due to the fact that big shower clouds were in the vicinity, but were moving so slowly and dissipating equally slowly, that the record was stopped.

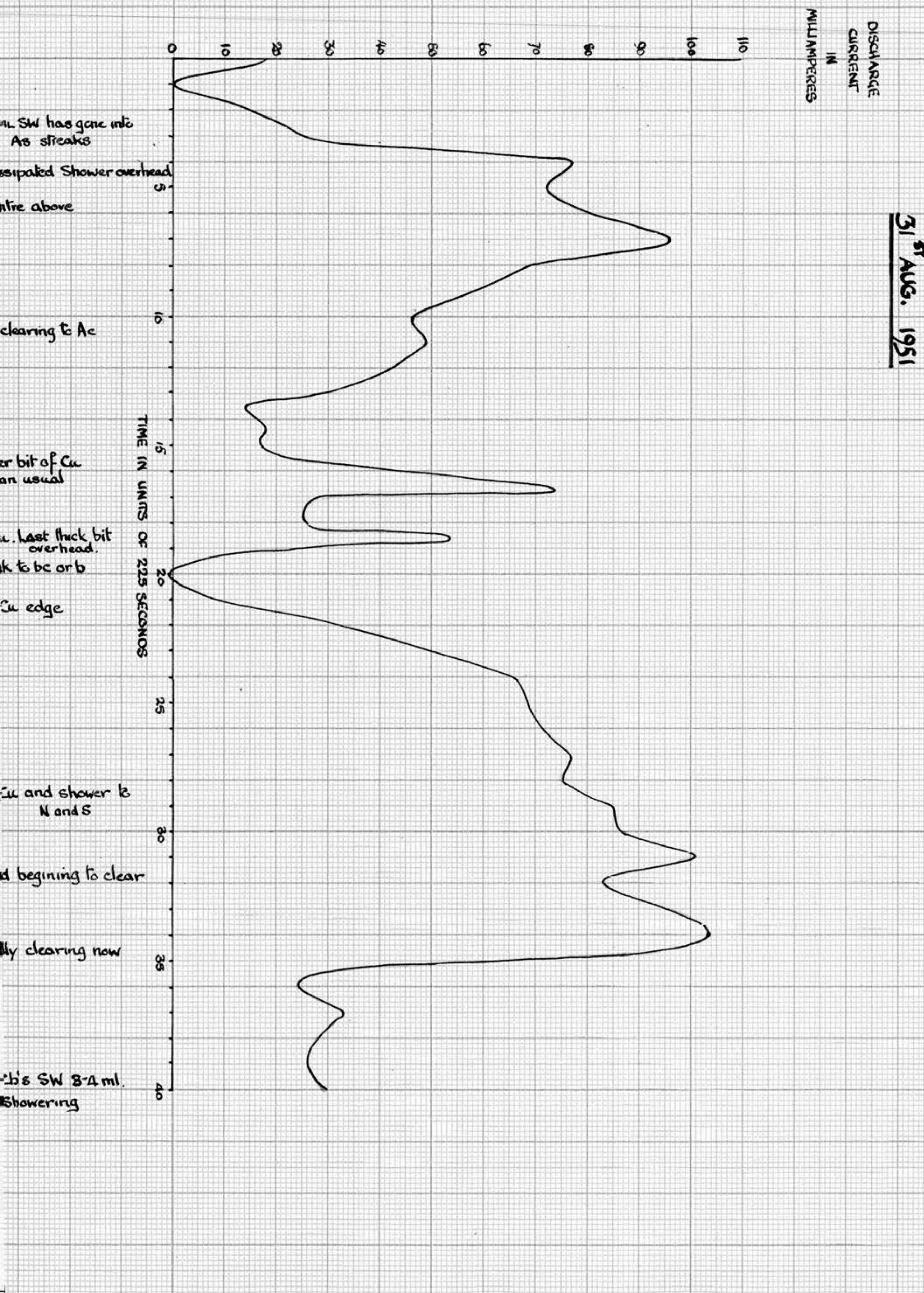
This graph did not require to be normalised as the HT batteries were changed during the afternoon, the slow change of base line ceasing with the change.

31ST AUG 1951



31st AUG. 1951



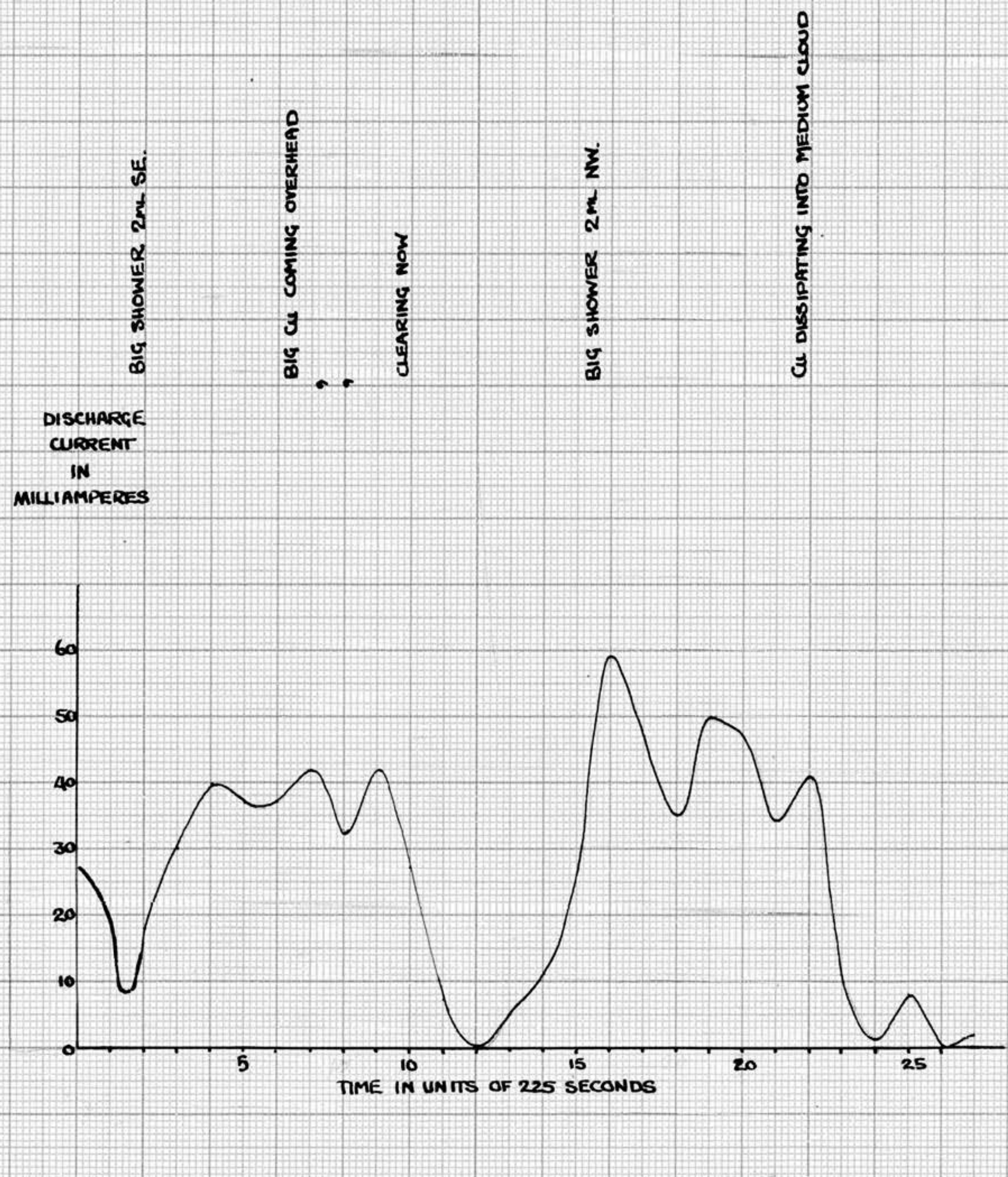

31st AUG. 1951
DISCHARGE CURRENT IN MILLIAMPERES
0
10
20
30
40
50
60
70
80
90
100
110
TIME IN UNITS OF 2.25 SECONDS
5
10
15
20
25
30
35
40
al SW has gone into As streaks
ssipated Shower overhead
ntre above
clearing to Ac
er bit of Cu
an usual
u. Last thick bit overhead.
k to bc or b
Cu edge
Cu and shower to N and S
d begining to clear
lly clearing now
b's SW 8-4 ml.
Showering

<u>1st Sep:</u>

Wind: SW. Force 3-4. Gusts 5-6.
Cloud: $^8/_{10}$ broken and torn cumulus.
(High winds aloft.)

This graph shows the passage of a slight shower over the tree, followed by the near approach of a big shower that dissipated into mammato-cumulus overhead.

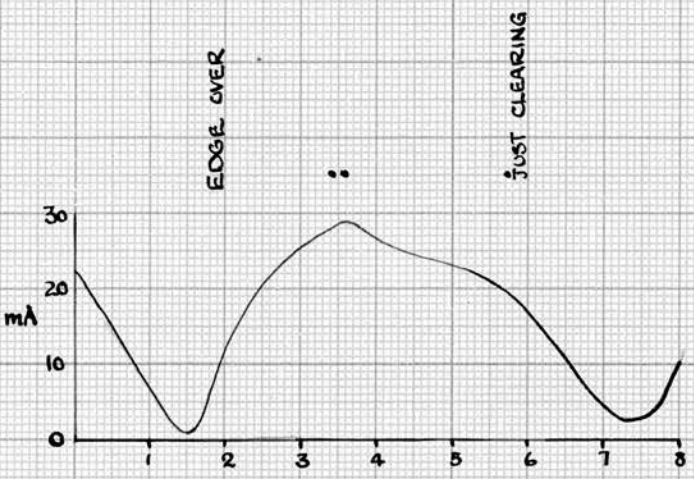
1st SEPT. 1951



The last Graph:

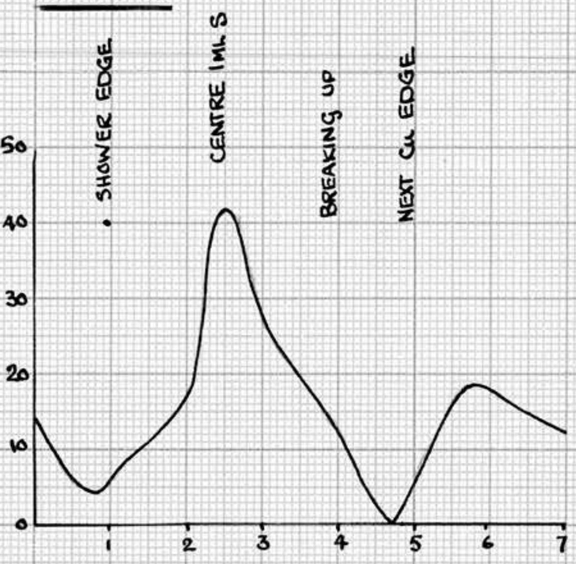
This graph shows a selection of individual clouds, recorded over short periods and included in the Table of Results.

17th JUNE 1951



SMALL SHOWER   BASE 1500'   TOP 12000'

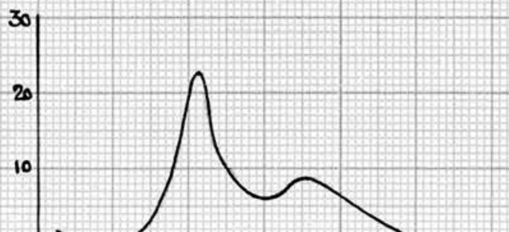
20th AUG.



SHOWER, CENTRE TO S. BASE 4000' TOP 10-12,000'
SHOWER RAIN TO S.

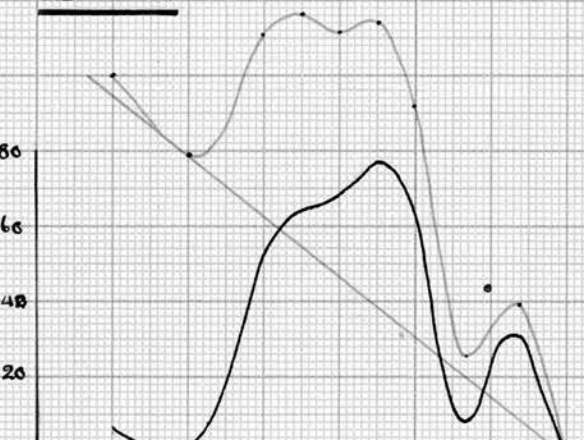
HORIZONTAL TIME SCALE IN UNITS OF 225 SECONDS
VERTICAL DISCHARGE CURRENT SCALE IN MILLIAMPERES

27th AUG.



PASSAGE OF A SMALL CUMULUS
A NEAT ISOLATED CLOUD
BASE 3000'   TOP 9000'

28th AUG.



CUMULUS   BLACK BASE 3000' TOP 10-12,000'

E E

Extract of clouds that did not pass overhead.

No.	Date	Cloud Type	Precipitation	Cloud Base	Cloud Top	Discharge Current. Max. Current mA.	Total Discharge Coulombs.	Discharge Current. Time taken $\times 10^3$ sec.	Average Current mA.	% of max.	Remarks.
7*	31 Aug	Cu	-	-	-	100	169	3.02	56.0	56.0	2 ML. SSW shower.
10*	10 July	Thunderstorm	Drizzle	-	-	91	278	5.63	49.4	54.3	2 Ml. N and S 2 clouds.
11*	25 June	Thunderstorm	-	-	-	84	226	4.73	47.7	36.8	4 Ml. E. Ci above.
14	20 Aug	Cb	-	-	-	65	104	2.79	37.2	57.2	3 Ml. SE growing.
15*	27 Aug	Thunderstorm	Drizzle	-	-	63	253	8.27	30.6	48.6	2-3 Ml. E.
16	1 Sep.	Cb	-	-	-	59	82.7	2.70	30.6	51.9	2 Ml. NW.
17*	10 July	Thunderstorm	-	-	-	51	73.8	2.54	29.1	57.1	3 Ml. N.
21	20 Aug	Cu	Slight Rain	4000	12,000	42	16.5	0.841	19.6	46.7	1 Ml. S centre.
25	31 Aug	Cu	-	3500	12,000	29	13.2	1.24	10.6	36.6	To S.
26	31 Aug	Cu	-	3000	10-12,000	25	19.0	1.24	15.3	61.2	½ Ml. S.

* Indicates chart with "normalised" base line.

F F

Extract of Clouds that passed overhead.

No.	Date	Cloud Type	Precipitation	Cloud Base	Cloud Top	Max Current mA.
1*	25 June	Cb	Heavy rain	-	-	145
2*	31 Aug	Cb	Heavy rain	-	-	142
3*	25 June	Cb	Heavy rain	-	-	135
4*	25 June	Cb	Heavy rain	-	-	120
5	31 Aug	Cb	Rain,drizzle	-	-	104
6	27 June	Line AsNs	Drizzle,rain	800	-	103
8	31 Aug	Cu	Drizzle	-	-	96
9	18 June	Cb	Rain,drizzle	2000	-	95
12*	31 Aug	Cu	-	3000	10-12,000	78
13	31 Aug	Cu	-	-	-	74
18	20 Aug	Cu	-	4000	10,000	46
19	20 Aug	Cu	Rain	-	-	42
20	1 Sept.	Cu	Drizzle	4000	10,000	42
22	10 July	Cu	Slight Rain	-	-	41
23	18 June	Cu	-	3000	12-14,000	35
24	17 June	Cu	Rain	1500	12,000	29
27	27 Aug	Cu	-	3000	9000	23
28	31 Aug	Cu	-	-	12,000	16

* Indicates chart with "normalised" base line.

Discharge Current.

Total Discharge Coulombs	Time Taken x 10^3 sec.	Average Current mA	% of max.	Remarks
819	9.13	89.7	61.8	Three clouds together.
250	4.05	62.2	43.8	-
Part of Cloud No. 1.				
- - -	-			
240	3.78	63.4	61.0	Slow moving.
188	3.20	58.8	57.1	Slow moving weak front.
148	3.29	45.0	46.9	Dissipating overhead.
182	3.92	46.4	48.9	Dissipating into As.
40.4	0.90	44.9	56.9	-
58.1	1.38	42.1	56.9	-
46.3	1.35	34.3	74.6	Thick band of Cu's.
24.6	1.67	14.7	35.0	-
70.8	2.47	28.7	68.4	Smallish.
44.3	2.16	20.5	50.0	-
29.2	2.92	10.0	28.6	-
24.2	1.40	17.3	59.5	Small Shower.
3.26	0.45	7.23	31.4	-
5.90	0.79	7.48	46.8	Base broken up.

						Discharge Current.		Discharge Current.			
No.	Date	Cloud Type	Precipitation	Cloud Base	Cloud Top	Max.Current mA	Total Discharge Coulombs	Time Taken x 103 sec.	Average Current mA.	% of max.	Remarks.
1*	25 June	Cb	Heavy Rain	-	-	145	819	9.13	89.7	61.8	Three clouds together.
2*	31 Aug.	Cb	" "	-	-	142	250	4.05	62.2	43.8	-
3*	25 June	Cb	" "	-	-	135	-	-	-	-	-
4*	25 June	Cb	" "	-	-	120	-	-	-	-	-
5	31 Aug.	Cb	Rain,drizzle	-	-	104	240	3.78	63.4	61.0	Slow moving.
6	27 June	Line AsNs	Drizzle,rain	800	-	103	188	3.20	58.8	57.1	Slow moving weak front.
7*	31 Aug.	Cu	-	-	-	100	169	3.02	56.0	56.0	2 Ml SSW shower.
8	31 Aug.	Cu	Drizzle	-	-	96	148	3.29	45.0	46.9	Dissipating overhead.
9	18 June	Cb	Rain,drizzle	2000	-	95	182	3.92	46.4	48.9	Dissipating into As.
10*	10 July	Thunderstorm	Drizzle	-	-	91	278	5.63	49.4	54.3	3 Ml N and S. 2 clouds.
11*	25 June	Thunderstorm	-	-	-	84	226	4.73	47.7	36.8	4 Ml E. Ci above.
12*	31 Aug	Cu	-	3000	10-12,000	78	40.4	0.90	44.9	56.9	-
13	31 Aug	Cu	-	-	-	74	58.1	1.38	42.1	56.9	-
14	20 Aug	Cb	-	-	-	65	104	2.79	37.2	57.2	3 Ml SE growing.
15*	27 Aug	Thunderstorm	Drizzle	-	-	63	253	8.27	30.6	48.6	2 - 3 Ml E.
16	1 Sep.	Cb	-	-	-	59	82.7	2.70	30.6	51.9	2 Ml. NW.
17*	10 July	Thunderstorm	-	-	-	51	73.8	2.54	29.1	57.1	3 Ml. N.
18	20 Aug.	Cu	-	4000	10,000	46	46.3	1.35	34.3	74.6	Thick band of Cu's.
19	20 Aug.	Cu	Rain	-	-	42	24.6	1.67	14.7	35.0	-
20	1 Sep.	Cu	Drizzle	4000	10,000	42	70.8	2.47	28.7	68.4	Smallish.
21	20 Aug	Cu	Slight Rain	4000	12,000	42	16.5	.841	19.6	46.7	1 Ml. S. shower centre.
22	10 July	Cu	Slight Rain	-	-	41	44.3	2.16	20.5	50.0	-
23	18 June	Cu	-	3000	12,-14,000	35	29.2	2.92	10.0	28.6	-
24	17 June	Cu	Rain	1500	12,000	29	24.2	1.40	17.3	59.5	Small shower.
25	31 Aug	Cu	-	3500	12,000	29	13.2	1.24	10.6	36.6	To S.
26	31 Aug	Cu	-	3000	10-12,000	25	19.0	1.24	15.3	61.2	½ Ml. S.
27	27 Aug	Cu	-	3000	9000	23	3.26	0.45	7.23	31.4	-
28	31 Aug	Cu	-	-	12,000	16	5.90	0.79	7.48	46.8	Base broken up.

* Indicates chart with "normalised" base line.

Discussion of Results:

The first and most striking observation to be made from these results is the magnitude of the point discharge currents. In this case of an isolated pine tree, the discharge current is greater, by a factor of about one thousand, than any of the measurements so far made by other observers.

If it is assumed that a square array of trees, similar to that used in this experiment, existed, with a separation of 100 metres, then the discharge current per square kilometre in thunderstorm conditions would be of the order of 10 amperes. Further if the spacing of the square array is reduced so that each tree is separated from its neighbours by a distance equal to twice its height, then the discharge per square kilometre would attain a value of 100 amperes. This choice of spacing corresponds to the practice employed in the erection of lightning conductors and is verified by the experiment reported hereafter. These two calculations indicate that the thunderstorm causes an electrical exchange between cloud and ground of very much greater quantities of charge than had originally been thought. The experiment carried out by Schonland (5) on a "bush" tree obtained a value of 0.18 amp/sq. km.

Previous workers have assumed that the lightnign flash itself played a significent part in the electrical exchange in a thunderstorm. In view of the evidence of the discharge currents reported here it can be seen that the charge brought down by the flash (average - 20 coulombs) is in fact of minor importance.

A certain amount of criticism of the Wilson theory of charge separation in the cloud and the rain drop charge, has been based on the lack of evidence of the necessary amount of charge being available. The Wilson process to be of importance is considered as having to be highly efficient. The existence of such large discharge currents in trees indicates that there is almost a super abundance of positive charge available.

This space charge is available to be picked up by the falling raindrops in the manner described by Professor Wilson. The drops themselves therefore arrive at the ground with a nett charge of opposite sign to the existing potential gradient. This charge is gained by ion capture. The Wilson process in this case need not be very efficient therefore. Due to irregularities in the distribution of the space charge caused by turbulence and the distribution of the point dischargers below the cloud, the potential field will also exhibit local irregularities. The nettcharge on a raindrop may therefore have values that bear no relationship to the potential gradient measured at the ground.

In order to maintain such a large discharge current however it must be assumed that the cloud itself is separating charge at a greater rate than is required for the production of the lightning flashes alone. Wilson (8) calculated the charging rate for a cloud immediately after a flash, to be about 3 amperes. He also indicates how this current may be the current running through the cloud at times other than immediately after a discharge by lightning.

If the point discharge from trees at the earth's surface is taking place at 10 Amps. per sq. Km., then the cloud must be neutralising this dissipation current at an equal rate, since the potential gradient can attain a steady value for quite long periods between flashes. The normal current through the cloud must therefore be of the order of 15-20 amps. for a small thunderstorm. This rough calculation infers that the Wilson process must therefore be even more efficient within the cloud itself than was previously considered necessary.

The improbability of the Wilson process being highly efficient within the cloud, and the neutralisation of this large amount of positive charge at the base, lead to an interesting possibility. It is one indeed which would explain the presence of a positive charge concentration within the base of the cloud. In all the standard diagrams of the charge distribution in thunderstorms, a small volume of positive charge is always indicated in the base of the cloud. Simpson's water drop splitting theory is usually considered as explaining this feature of the thunderstorm. Invariably this positive charge volume is indicated as existing where the maximum vertical connection is taking place. This positioning is consistent with the requirements of the Simpson theory.

It could however be argued that, since the positive ion mobility in air is small and the vertical air currents so rapid, the convecting air takes a large proportion of this point discharge current into just such a position in the cloud. Further convection to the top of the cloud, would then produce a significent addition to the positive charge distribution in the upper layers of the thunderstorm.

The conductivity being higher at the top of a cloud than at the base, ensures that the rate of dissipation of an accumulated charge is greater in that region. In order to maintain a steady state of electrical activity, the separation of charge, by the Wilson process, must be more efficient for positive than for negative charges. This does not appear to be a reasonable solution, as the balance of movement of the charge carriers - the precipitating droplets and cloud droplets - is heavily weighted in favour of the negative carriers. The possibility that the up-draught, in the cloud itself, is responsible for a considerable proportion of the positive charges accumulated at the top of the cloud, is therefore very attractive.

The charging of the lower pole of the cloud would be facilitated by such a process. The increased field, due to the arrival of the point discharge space charge at the top of the cloud, would immediately increase the efficiency of the Wilson process for the falling droplets. The Wilson process within the cloud is thus no longer of necessity highly efficient in either direction.

With the large quantities of charge released at the earth's surface a new conception of the thunderstorm must be devised. In order to maintain the well established ideas as to the outward effects of a thunderstorm, large amounts of charges of both signs must be considered as being well mixed within the cloud. It is now reasonable to assume that the actual effects of a thunderstorm are brought about not by the efficient separation of a large proportion of the charge available, but by the inefficient separation of a small proportion of the total charge, which is fairly evenly distributed within its volume. Thus it would appear that the concentration of sufficient charge within the cloud to produce a discharge is more a matter of chance than an essential part of the exchange process between the earth and the atmosphere.

The evidence suggesting that thunderstorms in South Africa are most likely to discharge within the cloud itself and have shown no indication of a positive pole in the cloud base might be explained by these observations. The tropical or sub-tropical thunderstorm has normally a much higher base than in this country. The point discharge currents consequently have a much greater opportunity of becoming evenly distributed in space. A large and evenly distributed space charge blanket would thus shield the earth and so reduce the probability of a discharge to earth. Similarly, after a discharge takes place in a cloud at these heights, the potential gradient at the earth's surface would remain mainly unaltered, as both a positive and a negative pole would have been removed. The positive space charge thus would not indicate its presence so clearly, in the potential gradient change, as to give the impression of the existence of a lower positive pole in the cloud.

The reason for the reversal of the sign of the potential gradient after a lightning flash, ascribed by Whipple and Scrace (4) to the space charge blanket left below the discharged negative pole of the cloud, is made quite clear by the evidence of this research work. The assumption of the existence of a positive pole in the base of the cloud becomes unnecessary.

The observations of such large discharge currents now leads to a difficult question. Does the activity of the thunderstorm depend on the number and exposure of the natural point dischargers below it ?

If the original conception of the electrical exchange holds, then the point dischargers are responsible for a large dissipation current at the lower pole of the thunderstorm. If the point dischargers are responsible also for an up-draught of positive ions as proposed, then they may be responsible for some of the separation of charge. In both cases the activity of the thunderstorm will be affected by the efficiency of the point dischargers below it.

The conception of the point dischargers as being responsible for a dissipation current only, will be taken here as being the correct one. Due to the general mixing of the positive ions, by turbulence and mutual repulsion, below a thunderstorm, it is thought that the discharge current space charge will be evenly distributed in the horizontal plane above 1000 feet. There will be exceptions in the case of the more violent up-currents.

Under these circumstances the current density of the dissipation current is the important factor in the electrical exchange. Can it be shown that this current is independent of the point dischargers causing it ?

An experiment could be devised to find the value of the current density, by the use of a square array of similar points sited on a moor. This experiment would however require much time and equipment. A close approximation to the conditions however can be made in the laboratory and is reported in the next section.

The Needles Experiment:

In the electrical exchange between a thunderstorm and the ground, a steady state of point-discharge current and space charge, must be set up. The potential existing at the base of the cloud must determine the value of this steady state. The process of ionisation in the air itself and the recombination of ions may be ignored in an approximate determination of this steady state.

If the electric field set up by a thunderstorm is such that point discharge takes place, then we can reasonably assume that above 1000 feet the space charge so liberated, will be uniformly distributed in a horizontal plane, by wind, turbulence, and mutual repulsion. The space charge distribution with height will become such that the combination of the electric field due to the cloud and that due to the space charge itself, will cause a steady current density to flow from the ground to the cloud. If the current does not become a constant then a collection of charge would take place between 1000 feet and the base of the cloud, such that the space charge field would eventually stop the point discharge. If the point discharge does not produce sufficient charge to replace the space charge removed by the cloud, then the field at the discharger will increase, and with it the current. This process will continue until such time as a steady state is attained or a spark (lightning flash) takes place.

This form of reasoning leads to the conclusion that for any electric potential at the base of the cloud, a fixed point discharge current density must flow from the ground. The value of the current density is determined solely by the potential at the cloud base and the exposure of the point dischargers below it. Further this current density is a constant with height above approximately 1000 feet.

It would appear therefore that the number and exposure of the point dischargers may affect the value of this steady current. Trees, adequately well spaced may be expected to discharge as described in the previous experiment, giving currents of the order of magnitude of milliamperes. The trees will then produce a current of density of large magnitude. In the absence of trees, blades of grass or heather on a moor will act as point dischargers.

The previous experiment has shown that the discharge from trees in a square array of 100 m. separation, would give a current of 10 amp/sq. km.. Schonland's calculations give a value of 0.18 amp/sq. km. for small "bush" trees. Calculations based on unpublished work by J. Paton, (9) indicate approximate discharges from grass of 1-2 amp/sq. km.

These figures indicate that the current density varies according to the type of ground over which the thunderstorm takes place. If this is the case then a thunderstorm having attained a definite stable state of activity over open moorland, will, on moving over park land with scattered trees, show a marked decline in activity. Conversely an active storm over park land will show an increase in activity on moving over moorland or the sea.

So far as is known no weather observer has yet noticed and remarked upon the occurrence of such a change in thunderstorm activity. It might therefore be assumed that current density is in fact a constant and independent of the exposure or number of the point dischargers. This assumption would infer that Nature herself has in general supplied an adequate number of suitably exposed points over all the land. Exceptions - such as the desert - must exist as well. This assumption is not quite so sweeping as it appears to be. The height of the lower pole of a thunderstorm is normally one or two kilometers. The height of trees and bushes and other point dischargers is thus insignificant compared with that over which the electrical field is distributed, corresponding only to a "roughening" of the earth's surface.

A laboratory experiment was carried out to see if any support for this conclusion could be obtained. By varying the number of point dischargers in a defined area, the effect of varying the "roughness" of the discharging surface may be investigated.

The Experiment:

A brass disc (6 inches in diameter, $\frac{1}{4}$ inch thick with rounded edges) was connected to a -4 Kv. E.H.T. power supply. This electrode represented the thunderstorm's lower pole. A similar paxoline disc, drilled (72 drill) in a square array, of $\frac{1}{4}$ in. spacing, and covered with a sheet of aluminium foil, represented the earth's surface. These two discs were supported on machined polystyrene blocks, ensuring a fixed and even separation of the two electrodes.

Steel needles (No. 8 Betweens), fixed in the drill holes in the paxoline disc by a hard wax, were raised to a fixed height above the aluminium foil on the "earth" disc. These needles represented the trees. The base of the pins, when in position, were immersed in a mercury bath, thereby making a good electrical contact with an "earth" wire. The "earth" wire was connected, via a Cambridge $\pm$ 60 uA Unipivot galvanometer, to the E.H.T. power supply earth.

In order to define a definite area, in which the point discharge current may be measured, a "hedge" of needles was erected on the "earth" plate. The height of the "hedge" needles was made the same as that of the tree needles. In order that the hedge had no effect on the experiment the spacing between the needles was decreased until no point discharge took place at the measuring voltage.

With this simple apparatus, the point discharge current, or more correctly the corona current, was measured for various regular arrangements of varying numbers of needles. The results are very interesting and may have quite far reaching significance.

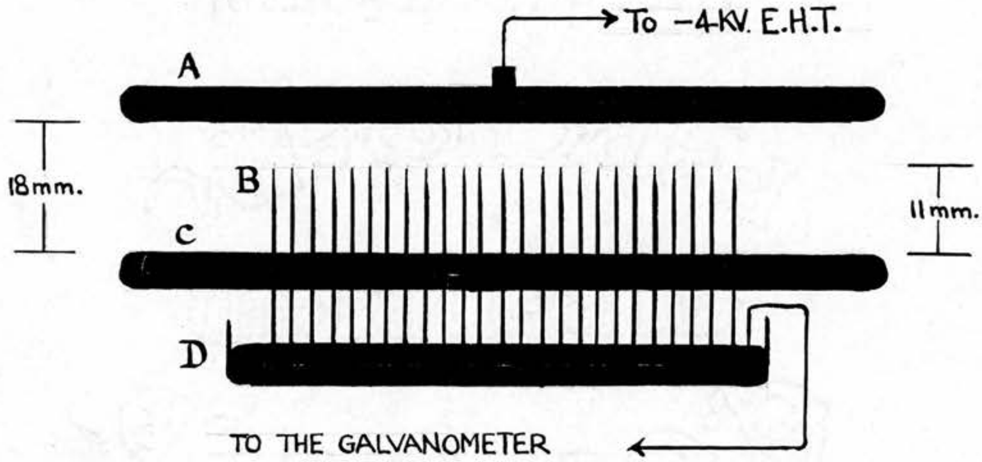
The Method:

A fixed voltage was chosen, such that the point discharge current (or corona current) from one single needle was of the same value as that measured by a platinum wire point discharger exposed in showery conditions - namely 1 - 2 uA. This voltage was kept constant for all the observations.

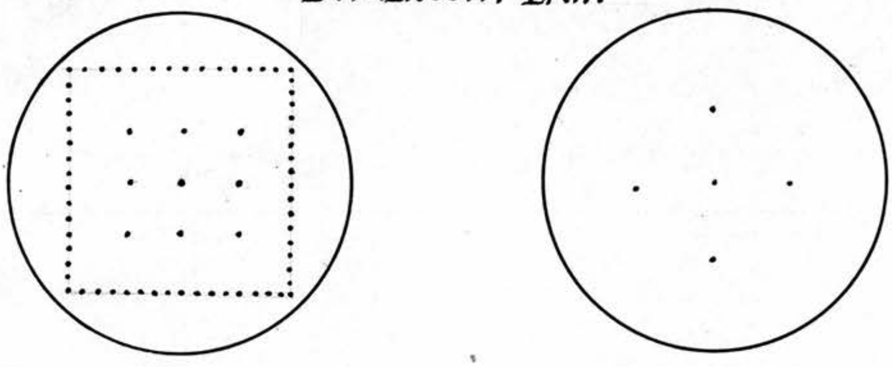
Measurements of corona current were then made for 1, 2, 3, 4, -----, 77. needles set out in a regular array within the "hedged" area. The height of the needles was made the same in each case. The earth disc was inverted over a flat brass plate and held away from it by equal distance-pieces, the needles were than tapped into place until they reached the plate, before being waxed in position.

THE NEEDLES EXPERIMENT

THE APPARATUS



A: "THUNDERSTORM BASE"
B: NEEDLES
C: "EARTH" ELECTRODE
D: MERCURY BATH



THESE TWO DIAGRAMS INDICATE THE LAYOUT OF THE NEEDLES ON THE EARTH PLATE IN THE SEPARATE EXPERIMENTS.

Results:

The results obtained are recorded in the two graphs overleaf.

By the introduction of an elevated point into the defined area, the electric lines of force were immediately concentrated on to the point. The electric field produced in the immediate neighbourhood of the needle point was then sufficient to start ionisation by collision, forming a burst corona discharge. The elevated point was then considered as shielding a definite area of the "earth" electrode. This area must correspond to the safe area about a lightning conductor. The introduction of more points increased the area of the earth plate shielded,by concentrating more and more of the lines of force on to the points, thereby removing them from the earth plate. This process was carried on until the entire area of the earth plate was shielded by the points.

Any further increase in the number of points could only mean a reduction in the area shielded by each point. This could also be regarded as a decrease in the number of lines of force ending on each point, producing a decrease in the electric field at the point. As the number of points used became very large, the electrical conditions tended more and more to return to those of a flat plate earth electrode.

This sequence of experimental conditions was used to represent the changes brought about by the movement of a thunderstorm of a fixed activity over desert, park land, and finally thick forest. The changes of corona current brought about may reasonably be supposed to indicate the form of variation to be expected from natural point dischargers in the equivalent circumstances.

It can be seen from the graph that by increasing the number of needles in the defined area from one to eight, an almost linear increase in corona current was observed. Each needle may be considered as having discharged independently, giving a definite burst corona current and shielding a fixed area of the earth plate.

Between 9 and 12 needles, the corona current increased progressively slower and tended to attain a steady value. Over this region the shielded areas may be considered as beginning to overlap slightly. An increase in the number of needles did not therefore mean a proportional increase in the shielded area.

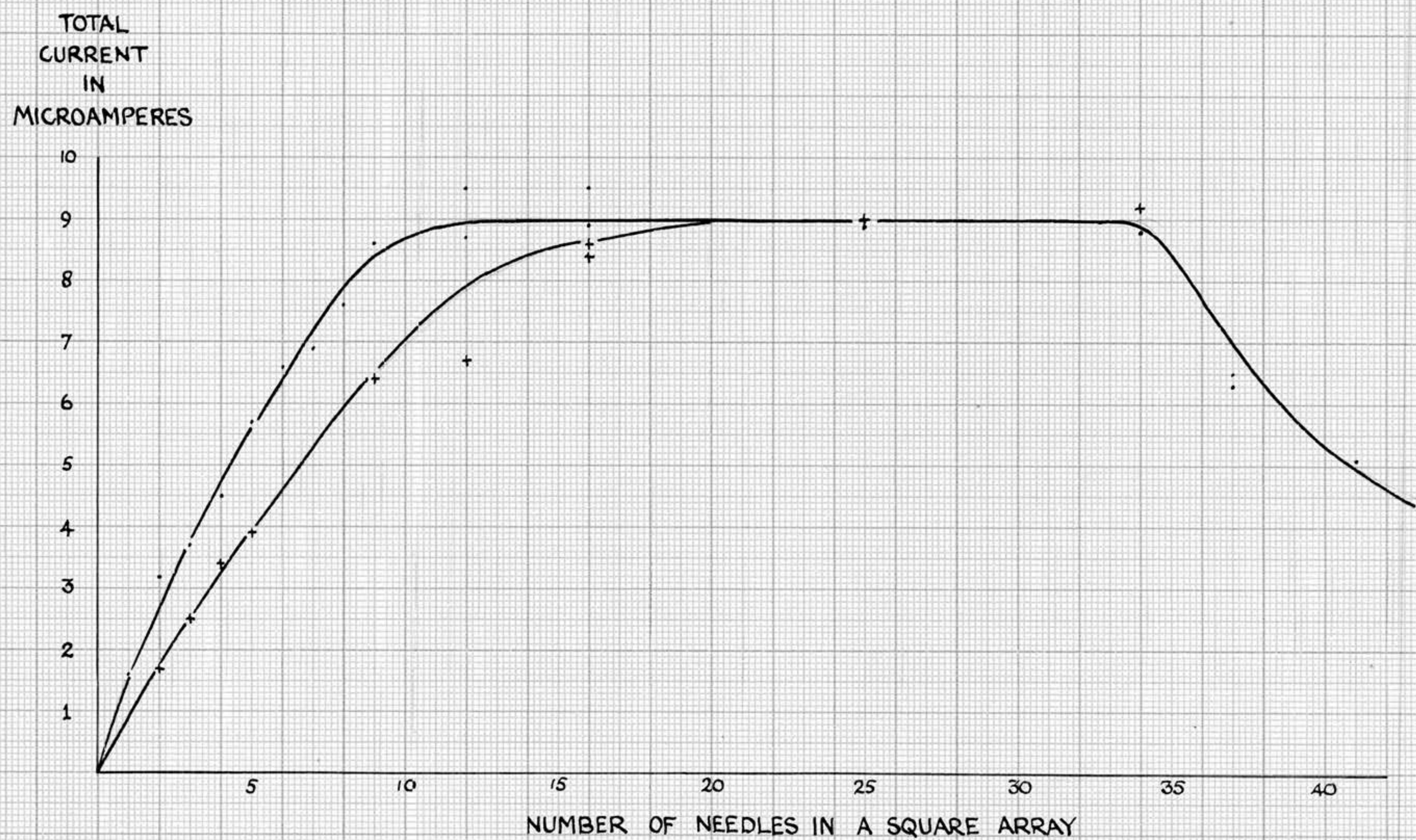
Further increase in the number of needles, from 12 - 24, caused increased overlapping of the shielded areas, or a reduction of the area shielded by each pin without overlap. The number of lines of force concentrated on each point was thus progressively reduced. Over this range the corona current remained constant. The current was thus independent of the number of needles used,and was considered as having attained a saturation value.

Between 34 and 36 needles, the current became slightly unsteady. This was due to the field at the needle points falling to a value that was critical for the maintenance of burst corona. Occasionally a needle point failed to give a burst corona, the discharge degenerating into the oscillatory streamer corona. Small variations in the total corona current were observed over this range.

When the number of needles was increased beyond 36, the corona current fell off. With 77 needles in the area, the current measured was + o.l uA, the reading error of the galvanometer. Over this range the number of lines of force at each point was only capable of maintaining streamer corona discharges. Due to the number of needles involved, the oscillatory nature of the streamer corona was masked and a steady discharge current could be measured.

This experiment was repeated many times. The same variation of corona current was observed on each occasion. The differences between the two sets of observations overleaf are due to changes in laboratory temperature and pressure. The lower

VARIATION OF CORONA CURRENT WITH THE NUMBER OF NEEDLES IN A SQUARE ARRAY



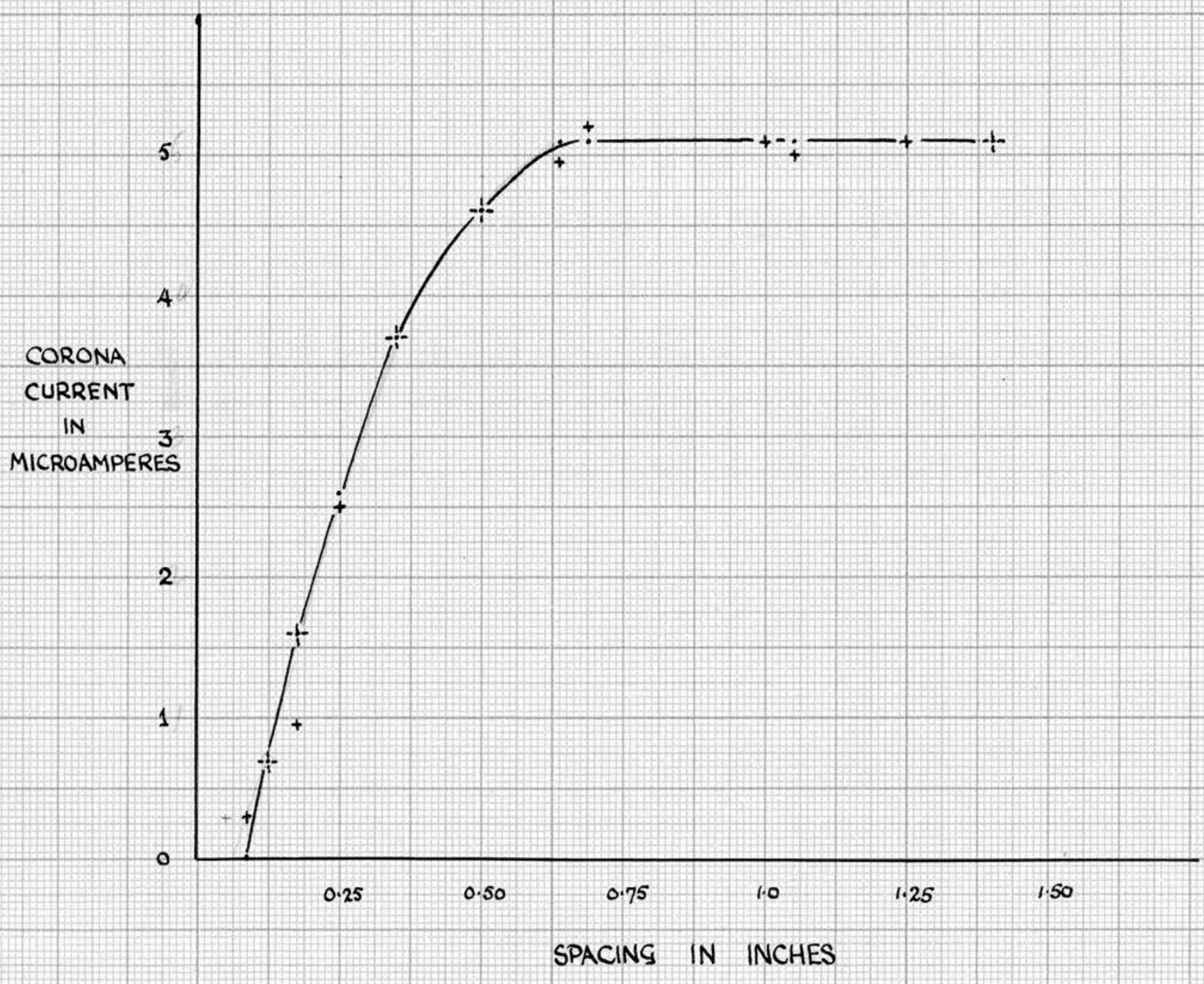
curve was obtained in a room temperature of approximately 50°F., the higher curve at 80°F. No observations of the atmospheric pressure were made.

One other experiment was carried out with this apparatus.

Using only five needles, arranged in a star formation, the variation of corona current with needle spacing was investigated. No "hedge" was required for this experiment. The results are shown in the graph overleaf.

It can be seen from the graph, that the corona current remained constant as the spacing of the needles was reduced from 1.5 inches to 0.75 inches. The current decreased with progressive reduction in spacing below 0.75 inches until it ceased altogether at a spacing approximately 0.1 inches.

CORONA CURRENT FOR FIVE NEEDLES WITH VARIABLE SPACING



Discussion of needles results :

The explanation for the existance for this "saturation" current may be described in the following manner:

The number of lines of force available is a fixed quantity, determined by the voltage used and the area enclosed by the "hedge". The concentration of the lines of force on to each point, provides at the point a definite volume in which ionisation by collision may take place, resulting in a burst corona discharge. This volume is determined by the field strength and the shape of the point. There is a minimum to the number of points required to obtain a concentration of all the lines of force in the defined area on to the points. No line now extends directly to the "earth" plate. This condition thus ensures the maximum volume possible at the points, in which burst corona may take place. An increase in the number of points produces a proportional decrease in the number of lines arriving at each point. This involves a decrease in the volume capable of maintaining burst corona, and a consequent drop in the corona current per point.

It would appear that the decrease in the burst corona discharge per point, is exactly offset by the increase in the number of points, thus producing a "saturation" current effect.

It has been shown (Loeb, 10), that an increase in the electric field at a point causes only a spread of the burst corona over the surface of the point. An increased discharge results from the spread of the discharging area, and not from an increased discharge over the area already maintaining burst corona. This is explained by the fact that the space charge produced by the corona determines a definite electric field within the discharge itself. An increase in the field strength must therefore be accommodated elsewhere.

It must be concluded therefore that once all the lines of force in the defined area are used to produce corona at the points, an increase in the number of points can only involve proportional decrease in the area of each point capable of producing a corona discharge.

In this way a "saturation" current is obtained, and within limits it is independent of the number of points used.

One or two interesting facts may also be noted from these two experiments.

The semi-vertical angle of the cone of shielding of each point may be calculated. The spacing of the needles when they first begin to interfere with one another may be taken from the graphs. The semi-vertical angle of the cone shielded may then be calculated. In both cases the angle is approximately 45°. This result agrees with the conclusions reached by those responsible for the erection of lightning conductors. In this case the calculation cannot be given with great accuracy, due to the restricted spacings available on the drilled plate.

The "saturation" current conditions break down when the semi-vertical angle of shielding is reduced to 17° - 18°.

These two facts indicate that for any defined area, the total point discharge will be a constant under certain conditions. If any number of point dischargers, of a fixed height, are arranged so that all the area is covered by the shielded cones from the points, such that the semi-angle of each cone does not exceed 45° or is less than 17°, we can conclude that the current density of point discharge will be a constant and determined only by the atmospheric electric field. It is not unlikely that Nature herself has provided point dischargers in such a way as to approximate closely with these conditions.

If it could be shown that the relative heights of the point dischargers was not of importance, then it could be concluded that the current density of point discharge current was in fact independent of the nature of the ground over which the thunderstorm travels.

It is thought that the height factor is not of as great importance as might be concluded from the research work so far carried out. The important factor may be the sharpness of the points themselves. An experiment to test the dependence of the point discharge on the height and sharpness of the point has yet to be devised.

The results of this last experiment may explain the observations of Chiplonkar (6). Using a point discharger of four points, Chiplonkar found that the discharge current was less than that observed with a single point of the same height for any fixed electric field. The experiment with the five needles provides the explanation. A wide spacing of the needles, thus ensuring that they did not interfere with one another, gave a discharge current of 5.1 uA. The discharge per needle was thus approximately 1 uA. A spacing of 0.125 inches gave a total discharge of 0.75 uA for five needles. In this case the current is less than would have been observed, had only one needle been used. It would appear that Chiplonkar's experimental arrangement corresponded to the latter case.

The conclusion drawn by Chiplonkar from his observations was that a similar effect, due to the proximity of the discharging points, would affect a tree. It may be however that this effect is only obtained when the area of the points, capable of producing point discharge is limited. In the case of a tree, the number of points of sufficient sharpness and consequently the area capable of acting as a discharging surface,is almost unlimited . If this is the case, then the tree will be more effective than a single point of equivalent height. This conclusion is confirmed by the main research work of this report.

Conclusions:

The use of a sensitive recording magnettometer to measure the order of magnitude of the point discharge currents in trees, has brought to light results that are much in excess of those forecast or considered as existing in nature.

Calculation of the total discharge from trees in a thunderstorm indicates a possible explanation of the existence of positive space charge volumes in the base of the cloud. Further it leads to the possibility that the charging of the upper pole of the thunderstorm by the Wilson process may be assisted by the point discharge taking place at the ground.

The second experiment with needles has brought to light the existence of a "saturation" discharge current from points, when their number and spacing in a definite area, is varied. This fact can be used to support the theory that the point discharge current from the ground during a thunderstorm is a constant. The steady value of the current density of the exchange between cloud and ground may be determined by the electric field of the thunderstorm alone and be independent of, within limits, of the number and exposure of the point dischargers below the cloud.

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To all those, too numerous to mention, who have helped and advised me throughout the last two and a half years.

Appendix :

A short account of the first year's work on the construction of a skin-effect magnetometer.

The type of instrument is described in the Journal of the Electrical Engineers, Pt. II. 94. (1947) p. 325.

This type of magnetometer was constructed, but unfortunately could not be made to attain an adequate sensitivity. The reasons for this were rather numerous. To attain the required sensitivity much work and the construction of rather expensive components would have been required. The project was therefore abandoned in favour of the instrument used, not however without a serious attempt being made to perfect the experimental apparatus already constructed.

The defects of the instrument were the following:

An oscillator, working the A/c bridge of the magnetometer elements, was required to be absolutely free from any second harmonic component in its wave form. Although four types of excellent oscillator were constructed, the second harmonic content of the output could not be reduced sufficiently to allow the true output signal to remain unaffected.

Because the magnetic fields to be measured were weak, the resistance change of the elements was so small that an extremely sensitive amplifier was required to detect the small output signal. Although an amplifier with a stable voltage gain of 10^7 was constructed, it was not possible to make it at the same time sufficiently selective to remove the second harmonic signal.

The use of transformers in the A/c bridge that were not sufficiently well matched made the removal of a second harmonic signal impossible. The description of the prototype instrument, stresses the importance of the matching of these transformers.

In all, four oscillators, two amplifiers and four sets of magnetometer elements were constructed. Despite the trouble taken the required sensitivity could not be attained. The final sensitivity attained was 10^{-3} oersted/volt. output signal. This was deemed inadequate for the experiment.